Canadian Institute of
Guided Ground Transport
Queen's University
at Kingston, Ontario

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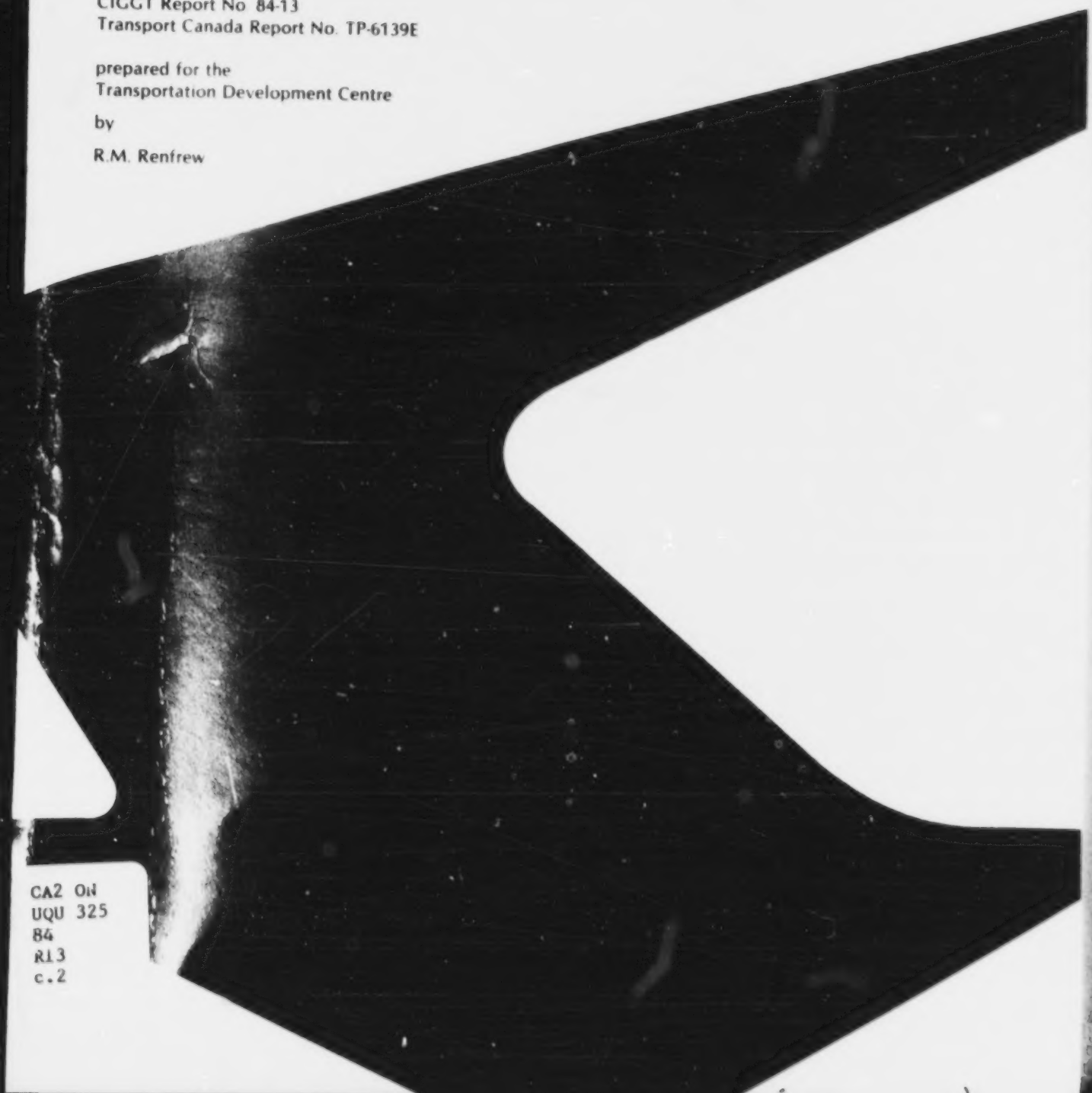
Transport Canada Report No. TP-6139E

prepared for the
Transportation Development Centre

by

R.M. Renfrew



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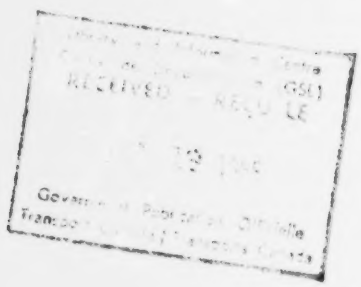
Transport Canada Report No. TP-6139E

RAILWAY TUNNELLING IN ROCK USING TUNNEL BORING MACHINES

prepared for
the
Transportation Development Centre

by

R.M. Renfrew



Canadian Institute of Guided Ground Transport
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17. Abstract

The importance of access to resource deposits in the Canadian Rockies and the Canadian Shield, plus the desirability of improving the existing rail alignments in the Rockies, indicates that significant reductions in tunnelling costs should be a research objective. In the past decade, the reliable use of tunnel-boring machines (TBMs) in hard rock has been demonstrated. New cutter designs and materials have produced improved machine performance. The combination of high-pressure water jets with conventional cutters has been demonstrated to achieve a large increase in production rates. Other technology, involving abrasive fluids, laser cutting and alternative machine configurations, appears to offer further opportunities for performance enhancement. This report examines TBM performance and the auxiliary systems which appear to be capable of integration with the TBM for higher productivity. The economic analysis shows that while the performance is substantially enhanced, the unit costs are not significantly improved. The project duration is generally shortened and this could yield important savings in costs of capital. Some of the technology research options are discussed in the context of acceptable cost and feasibility of demonstration in a commercial project.

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17. Résumé

La mise en valeur des richesses naturelles que recèlent les Rocheuses et le Bouclier canadien, ajoutée à la volonté de raccourcir certains tracés ferroviaires dans les Rocheuses, devraient encourager la recherche sur les moyens de réduire sensiblement le coût de réalisation des ouvrages souterrains. La fiabilité des machines de percement de tunnels (tunneliers) a été démontrée au cours de la dernière décennie, et leurs performances ont été nettement améliorées par l'emploi d'outils de coupe réalisés dans des aciers spéciaux. L'introduction d'une injection d'eau sous haute pression a permis d'augmenter la productivité des outils classiques; mais de nouvelles techniques semblent pouvoir rehausser davantage les productivités: fluides abrasifs, coupage au rayon laser et machines à configuration nouvelle. Le présent rapport examine les performances de ces machines à forer, et celles des accessoires capables d'en accroître la productivité. L'étude économique a montré que les coûts unitaires n'ont guère évolué, même si les performances se sont grandement améliorées. Par contre, les temps d'exécution sont généralement raccourcis, apportant d'importantes économies dans les coûts de premier établissement. Enfin, le rapport présente diverses options de recherche, élaborant sur leur faisabilité technico-économique et sur la possibilité de monter un projet de démonstration commerciale.

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EXECUTIVE SUMMARY

Tunnelling methods changed very little from the mid-1800s to the mid-1900s. The use of improved explosives, equipment and procedures greatly enhanced safety and productivity; however, there were no breakthroughs in mechanization.

The tunnel-boring machine (TBM) concept has been pursued during this century. It offers a safer, faster means of accurately boring a tunnel and has been very successful in soft ground and soft-to-medium rock.

The limited effectiveness of the TBM in hard rock has been a disincentive to its use. However, from the mid-sixties to the present, the performance of the TBM and the effectiveness of the rock cutters was steadily improved and the decision between TBM and drill-and-blast is now an economic one.

TBMs cannot be used indiscriminately. Some rock conditions are unsuitable for efficient TBM operation. Heavily fractured, shifting and extremely high-strength rock generally limits TBM efficiency at non-competitive levels. However, where rock strength and integrity, tunnel wall accuracy and finish, and the requirements for the length of tunnel (long) are appropriate, the TBM is very competitive.

The susceptibility of TBM performance to rock structure and consistency has led to a focus on cutter technology and to novel methods of fracturing rock. TBMs have been fitted with high-pressure water jets which are capable of cutting the rock face and inducing fracture at power levels lower than those of the unaided machine. The jets also cool and lubricate the edges of the cutters mounted on the TBM face. Such assisted cutting has been quite successful with selected rock conditions, and is consistently exploited in coal mining. If similar performance improvements could be obtained in hard rock, the TBM would be substantially cheaper than the conventional repetitive drill-and-blast repetitive technique.

High-powered lasers have been proposed, and demonstrated in laboratory conditions, for cutting rock. They are, however, very costly, inefficient, and not ready for continuous operation in a mine environment.

The study examined the water jet augmentation from both an operational and cost perspective.

The operational criterion of most significance is reliability. It is not clear that the technology is fully reliable but indications are that it can be made reliable at reasonable cost, provided operating procedures are adhered to.

The cost study showed a surprisingly neutral result. The actual dollar saving is negligible but the time to complete the tunnel can be significantly shorter.

The conclusions which can be reached at this time indicate that research should be directed to the following areas:

(1) A closer examination of high-pressure jets in concert with the conventional rock drill.

(2) Development of a TBM configuration which has the capability of starting into the rock face without creation of a major pilot tunnel by blasting. This would minimize the mobilization cost and make the TBM much more competitive for short tunnels. Most tunnels required in Canadian rail expansion will be relatively short (less than 3 km).

(3) Development of superior alloys and treatment of cutter steel to improve TBM operating cycles.

There are substantial advantages in using TBMs where rock conditions and logistics make blasting for track expansion a hazardous process (as in the Fraser Canyon). A specialized mechanical derivation of the TBM is definitely desirable for this purpose.

Another adaptation of the TBM, which combines the boring and lining processes into a single pass, has been studied and proposed for prototype development. This single-pass process greatly enhances the cost-effectiveness of the TBM. Where a lined tunnel is required for water control or structural integrity, the TBM is advantageous. These are important factors in transit tunnels.

The future developments identified relate to applications where the advantages of the TBM can be optimized -- primarily in terms of speed of tunnel completion.

SOMMAIRE ADMINISTRATIF

Les techniques utilisées pour le forage de tunnels n'ont guère évolué entre les années 1850 et 1950. Et même si l'emploi d'explosifs, d'équipements ou de méthodes plus perfectionnés ont permis d'accroître la sécurité et la productivité, aucune progression n'a été réalisée du point de vue mécanisation de la foration.

L'idée de construire des machines à découper des galeries souterraines (les tunneliers) sans l'emploi d'explosifs est née au 20e siècle. Ces machines ont apporté une sécurité, une rapidité et une précision accrue, en plus de maximiser les performances en terrains meubles et en terrains rocheux de résistance faible à moyenne.

Par contre, les contre-performances dans les roches dures ont jusqu'ici découragé une large utilisation de ces machines. Mais, depuis le milieu des années 60, leurs performances ont été grandement améliorées et leur efficacité est devenue telle que seuls des critères économiques président désormais au choix entre les techniques d'abattage avec et sans explosifs.

Toutefois, l'utilisation de ces machines doit faire appel à beaucoup de discernement. Tout dépend, en effet, de la qualité des terrains. S'il s'agit de terrains rocheux très fissurés ou instables ou de résistance très élevée, l'efficacité de ces machines chute à un niveau inacceptable, alors qu'elles peuvent être très compétitives quand une grande précision et une haute qualité de finition du profil sont exigées et quand les caractéristiques des terrains sont bonnes et les longueurs à percer suffisantes.

L'importance des paramètres de résistance et de cohésion des terrains attaqués a fait porter la recherche sur des outils plus performants et sur des techniques spéciales pour fragmenter les massifs rocheux.

C'est ainsi qu'ont été réalisés des tunneliers à injection d'eau sous forte pression, capables de fragmenter le front de taille à un coût énergétique bien moindre. De plus, l'injection permet de refroidir et de lubrifier les outils de coupe montés sur la tête d'abattage. Cette

méthode qui s'est révélée très efficace dans certaines qualités de roches est couramment utilisée dans les charbonnages. S'il était possible d'obtenir les mêmes performances dans les roches dures, ce procédé deviendrait plus économique que celui de l'abattage à l'explosif, à caractère répétitif.

Des techniques d'abattage au laser on été démontrées en laboratoire, mais elles sont très coûteuses, peu efficaces et ne se prêtent pas à une exploitation en continu dans les dures conditions d'utilisation en souterrain.

Notre recherche a porté sur l'emploi de l'eau sous pression, du point de vue technique et économique.

Le principal critère technique a été, bien sûr, celui de la fiabilité. Or, il n'est pas évident que cette technique soit totalement fiable; elle pourrait cependant le devenir à un coût raisonnable, à condition de s'en tenir aux méthodes de découpage préconisées.

L'étude économique a dégagé des résultats singulièrement neutres. Mais si, d'une part, il y a peu d'économies d'argent à réaliser, les économies de temps, elles, peuvent être importantes.

Les conclusions qui s'imposent à ce stade-ci sont que la recherche devrait poursuivre les objectifs suivants:

(1) examiner de plus près la technique de l'injection d'eau haute pression à l'appui des matériels d'abattage classiques;

(2) étudier une technique qui permette d'attaquer le front de taille directement, sans abattage préalable par explosif. Cette technique réduirait les coûts de mise en oeuvre et rendrait ces machines plus compétitives dans le creusement de tunnels relativement courts (moins de 3 km) comme ceux que nécessiterait l'extension du réseau ferroviaire canadien;

(3) mettre au point des alliages de qualité supérieure et des méthodes améliorées de traitement thermique des aciers de coupe.

Nombreux sont les avantages de pouvoir utiliser des tunneliers là où il serait hasardeux d'utiliser les techniques classiques à l'explosif, en l'occurrence le Fraser Canyon. Il serait donc éminemment souhaitable de réaliser une variante de ces machines, utilisable exclusivement dans le domaine considéré.

Une autre variante envisagée, et dont on propose de construire un prototype, est une machine qui réaliserait l'abattage en même temps que le revêtement des parois, ce qui augmenterait considérablement la productivité. Elle serait particulièrement utile là où le revêtement doit remplir les rôles d'étanchéité et de soutènement, notamment dans les tunnels routiers et chemins de fer métropolitains.

Les options envisagées concernent des applications où l'avantage de ces machines peut être optimisé, notamment du point de vue rapidité d'exécution.

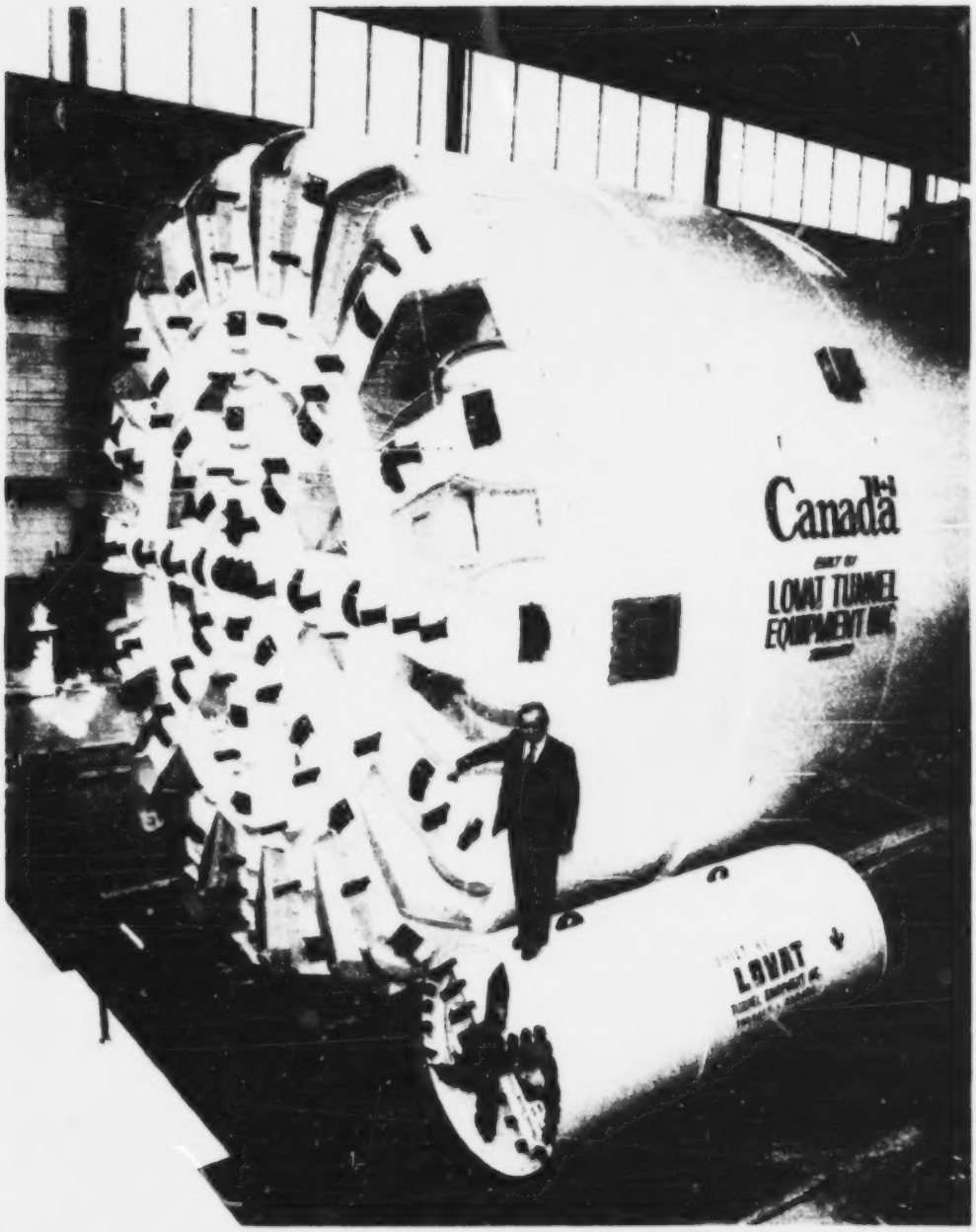

PLATE I

TUNNEL-BORING MACHINES DEVELOPED BY LOVAT TUNNEL EQUIPMENT INC.:

- large machine is the medium rock design for the Donkin-Morian mine access (Cape Breton)
- small machine is a typical soft-ground water/sewer tunnel design.

1. BACKGROUND

1.1 Railway Tunnelling in Canada

The Canadian Pacific Railway's transcontinental railway project of the 1880s was most remarkable because of its successful crossing of the Rockies. This required many tunnels, and in particular the famous Cathedral Mountain Tunnel which is probably the outstanding tunnelling achievement in railway history. Tunnels have been constructed in the Alps, which in some respects rival those of the CPR; however, builders of the Alpine tunnels enjoyed the benefit of technology improvements which were unavailable to the early Canadian pioneer railroaders.

In the 1980s and 1990s there will be a continuing high level of tunnelling activity due to the Tumbler Ridge project of BC Rail, the Rogers Pass project of Canadian Pacific, and a continuing requirement for system improvements and access to new resource developments.

The requirement for transit system tunnelling will continue in North America. In Canada there will be system extensions in Vancouver, Toronto and Ottawa which will involve tunnelling for at least part of the alignment. In the United States, Los Angeles will require a major tunnel development in the central region, while New York, Chicago, Boston and several other cities will continue to improve their systems by shorter tunnel links or extensions.

All of the significant railway tunnels will be in rock -- usually deep and high-strength. A large proportion of transit tunnels will be rock; however, they are likely to be in softer, sedimentary structures which are more easily handled than the geology of the Rockies. (Refer to Appendix D for an overview of the geology of the major rail corridors in Western Canada.)

Future Canadian natural resource price competitiveness will be strongly influenced by our ability to access mineral sources at acceptable cost. Equally, the high cost of urban transit system infrastructure must be reduced to permit a continuing high level of service in our cities. Since rail tunnel cost is in the range of $15,000 to $30,000 per metre, and transit tunnels are $50-$60 million per system-kilometre, cost reductions of 20-50 per cent represent a major savings potential. Cost

reductions of this magnitude have been demonstrated in a number of demonstration projects and specialized applications, such as sewer and water tunnels.

1.2 Tunnel Boring Machines (TBMs)

TBMs, variously called "shields" and "moles" in different configurations and geology, have been developed since Brunel's original Thames crossing project in 1820-1840. There are now manufacturers of TBMs in Europe, North America, Japan and Russia. TBMs have been used for transit tunnels in Caracas, Washington, Munich, Buffalo, Montreal and Paris in recent years. A 23 foot (6.67 m) diameter Robbins TBM is currently being used to bore part of the Rogers Pass tunnel, for CP Rail, in rock up to 18,000 psi strength. The expected rate is 25 metres/day.

The recently completed (1984) access tunnel to the Donkin-Morian mine in Cape Breton was bored using a 25 foot (7.58 metre) diameter Lovat TBM in rock up to 22,000 psi with average strengths of 7,000-14,000. Production rates were typically 20-25 metres/day.

The technology of TBMs is well established; however, they are not a panacea for tunnelling problems. The following factors affect whether or not a TBM is the appropriate choice.

1.2.1 Continuous Operation

There is a significant cost associated with access and set-up required to initiate TBM operation. This includes:

- driving the starting excavation (stub tunnel) to set up the TBM
- site access to move in a large machine; alternatively, site assembly of the TBM
- power supply (electrical).

Variation in the rock due to structure and type will affect the rate of boring. Cutter life is a function of rock characteristics. To change the cutters requires retracting the machine to provide working space at

the face. Conditions at the face may not be fully secure from loose rock, etc., adding to the difficulty of cutter change-out.

The TBM approach has a major advantage in that the spoil is generated at a uniform rate; however, continuous TBM operation is totally dependent on reliable muck removal.

The TBM is highly competitive in long tunnels. In a theoretical evaluation[2] it was shown that the TBM surpassed drill-and-blast (DB) at 6 km tunnel length for a 3.66 metre diameter tunnel in 15,000 psi rock. The theoretical advance rate was 2.4 metres/hour, and cutter life was assumed to be 500 hours. The theoretical evaluation was not an actual tunnel project, but it illustrates the sensitivity to a continuous process.

1.2.2 Non-circular Shapes

A circular tunnel is acceptable for transit applications because of the need to minimize "piston" effect in the tunnel and the requirement for a full passenger escape walkway.

However, railway tunnel design necessitates controlling the ventilation air flow by maximizing the piston effect, within practical limits. In addition, due to the 8 metre height provision for electrification clearance, a circular shape would generate a tremendous excess spoil volume. Several techniques are employed to achieve non-circular tunnels:

(a) A TBM can be used to cut the upper part of the tunnel. The invert is then excavated by bench-blasting. The Rogers Pass tunnel is being excavated in this way.

(b) Two-track tunnels can be formed by boring the centre and DB-excavating the sides to achieve a flattened horseshoe.

(c) In the Austrian method the roof arch is DB-excavated and rock-bolted to provide structural support. The lower half of the tunnel is then excavated by mechanical means. This sytem is limited in its application to lower-strength rock.

1.2.3 Minimization of Overbreak

A TBM typically generates a relatively smooth wall finish. The DB method fractures the rock for an excessive diameter. The loose rock from DB excavation generates excessive material from 50 to 100 per cent of the required tunnel volume. The tunnel wall will be rough. The disturbed strata may permit substantial seepage of ground water.

Tunnel ventilation is ineffective under these circumstances and exclusion of seepage is extremely difficult.

Where tunnel lining is required, a TBM offers significant advantages. The fact that the Rogers Pass tunnel will be lined was a major factor in the decision to use a TBM on that project.

1.2.4 Capital Cost

This is easily the most significant factor in the TBM/DB trade-off. Typical TBMs for soft-ground tunnelling (4.5-5.00 metre diameter) cost $2 million (Cdn) and more. The 20,000 psi rock TBM for the Donkin-Morian mine cost $10 million (Cdn, 1982). Since each large TBM tends to be a custom design, the front-end cost is not susceptible to production economies.

Higher strength rock requires a higher axial force TBM. Axial force capacity is the main determinant of machine cost.

Due to the risk of damage, and the uncertainties of the tunnelling business, most TBMs are amortized against one contract. A cash-flow analysis is required to decide on the financial benefits of TBM versus DB on a project-by-project basis.

1.2.5 Rock Stability

TBMs have been trapped by shifting rock or by squeeze pressure in high-stress rock. This can result in the total loss of the TBM.

1.2.6 Safety

The TBM is inherently safer than DB. If a lined tunnel is required, the TBM can be used to place the liner segments so as to virtually eliminate exposure to unlined tunnel walls.

TBM operation typically reduces rock fall risk and liberation of gases.

1.2.7 Summary

The use of a TBM is a site-specific decision. In general, a TBM will be competitive if:

- the tunnel is relatively long (typically 1,000-2,000 metres minimum)
- the geology is continuous and stable
- the tunnel shape is compatible
- a tunnel liner is required
- the productivity increase is high enough to offset the front-end capital cost.

1.3 Technology

1.3.1 TBM Development

The major hard rock TBM manufacturers are relatively few in number. A brief synopsis of their products is included in Table 1.1. Reference [3] provides a comprehensive survey.

It is clear that TBM development has occurred continuously during the past thirty years. No more than four or five companies today can be considered as serious developers.

The hundreds of machines which have been built and operated in a wide variety of rock conditions are adequate proof of the dependability of the basic machines.

TABLE 1.1

SUPPLIERS OF HARD ROCK TBMs

Supplier	Machine Types Available (date of original development)	Cutting Technique	Rock Strength (psi) Range of Applications
Atlas Copco (incl. Habegger equipment which is now produced under Atlas-Copco ownership)	Full face circular (1967) Full face roadheader for non-circular shapes (1972)	Employes separately rotating milling-type cutters which reduce significantly the axial trust required	4,000 to 45,000
Mannesman Demag.	Full face circular (1966)	Conventional cutter arrangement (disc or roller) on full rotating head)	4,000-60,000
Wirth	Full face circular (1969)	Conventional cutters	4,000-40,000
	Pilot bore/reaming full-face circular (1969)	Smaller pilot-bore by circular TBM ahead of annular bore trailing drag-bit cutters	10,000-15,000
Greenside/McAlpine	Full face circular or non-circular (1968)	Milling-type cutters movably mounted on a radial arm	8,000-35,000
Jarva Inc. (now a division of Atlas Copco)	Full face circular (1966)	Conventional cutters	6,000-66,000
The Robbins Company (Komatsu-Robbins)	Full face circular (1965)	Conventional cutters	1,000-50,000
	Full face roadheader (1977)	Conventional cutters	
Companies which have developed machines but are now inactive in this product:		Bade & Co. GmbH Calweld Dresser Industries Hughes Tool Co. Krupp GmbH Ingersoll-Rand Ltd Mitsubishi Thyssen Union Industrielle Blanzy-Ouest	

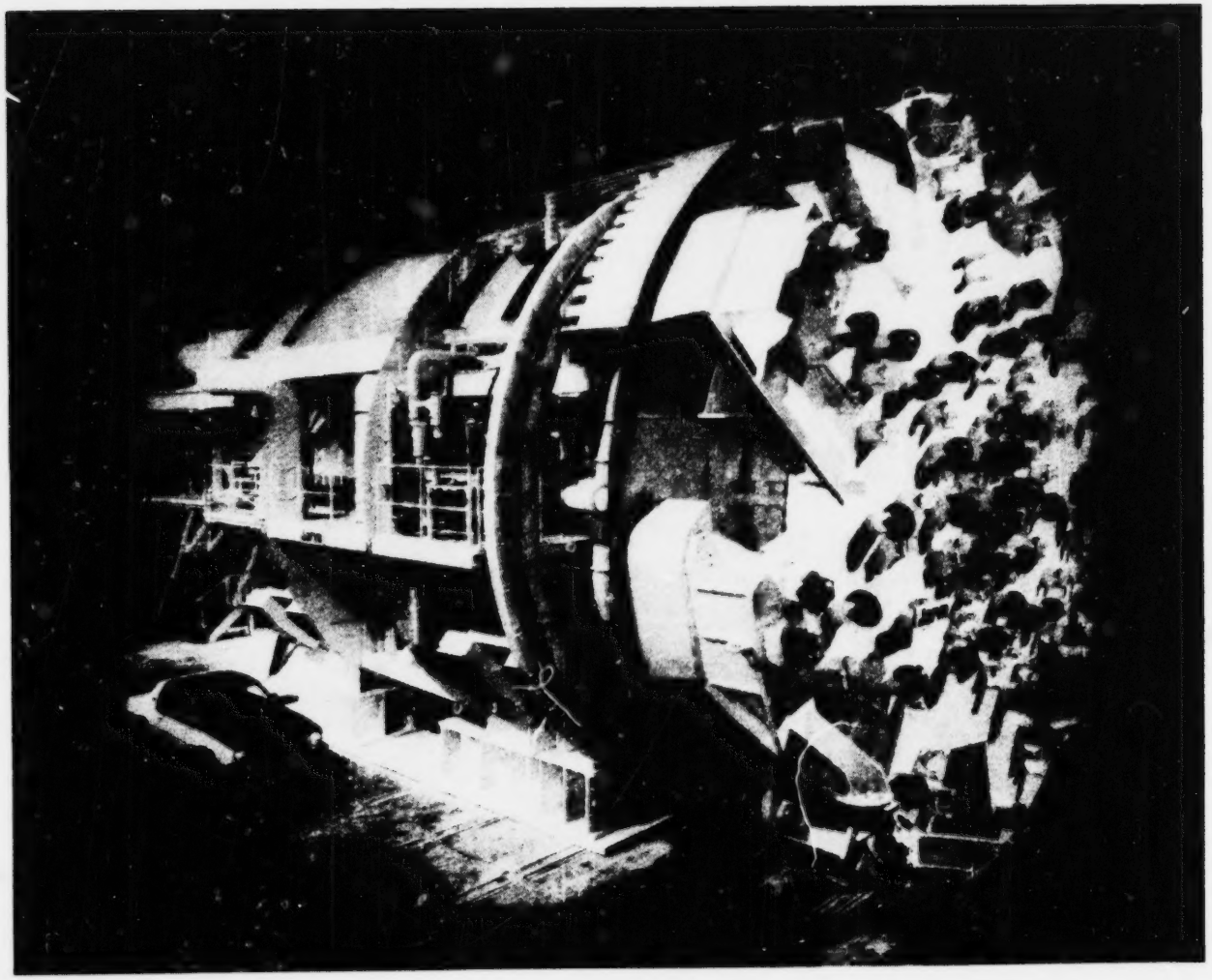

PLATE II

JARVA 9.8 METRE DIAMETER MACHINE:
. bored over 10 km of major water tunnel in Chicago

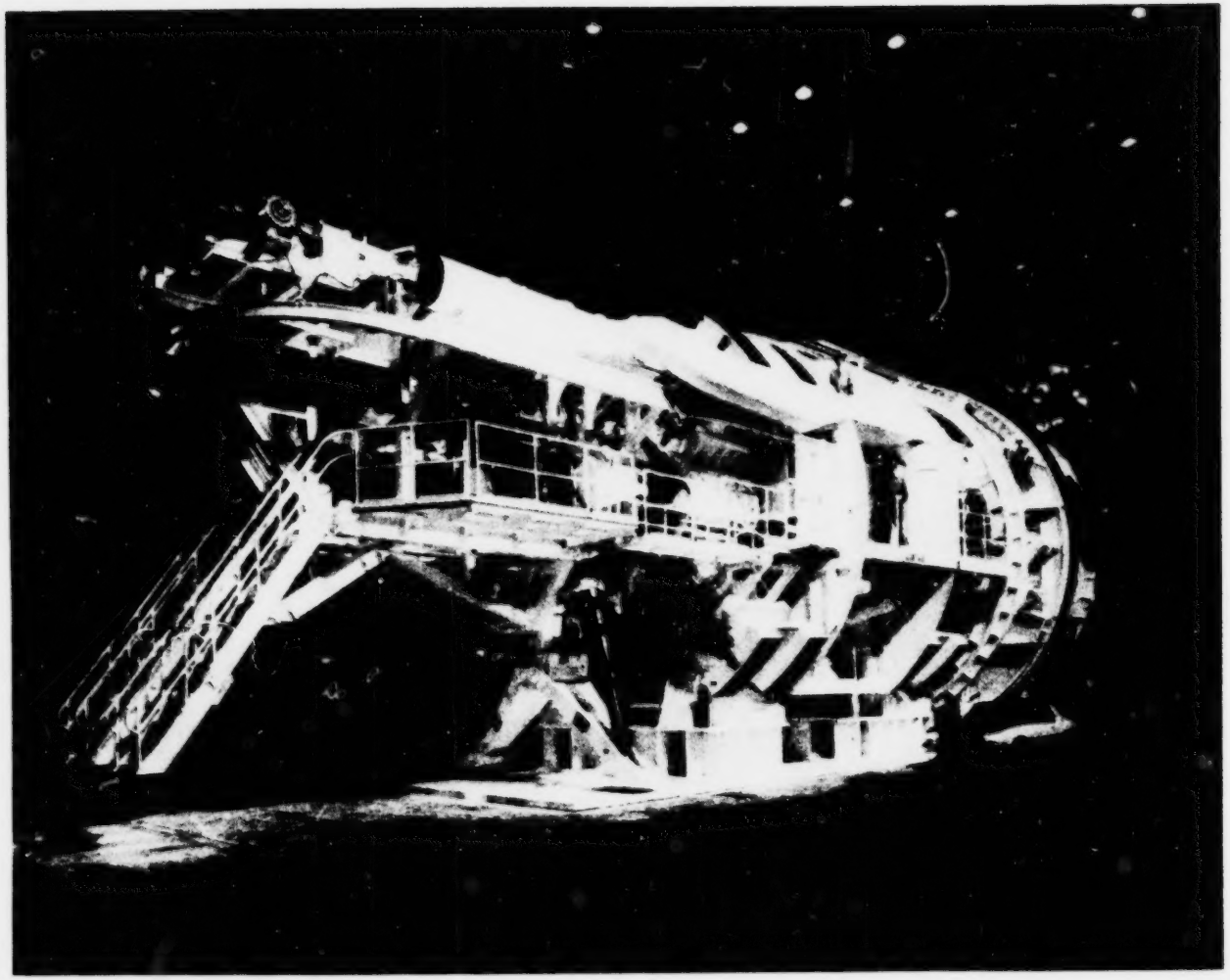

PLATE III

JARVA 9.8 METRE DIAMETER MACHINE:
. bored over 10 km of major water tunnel in Chicago

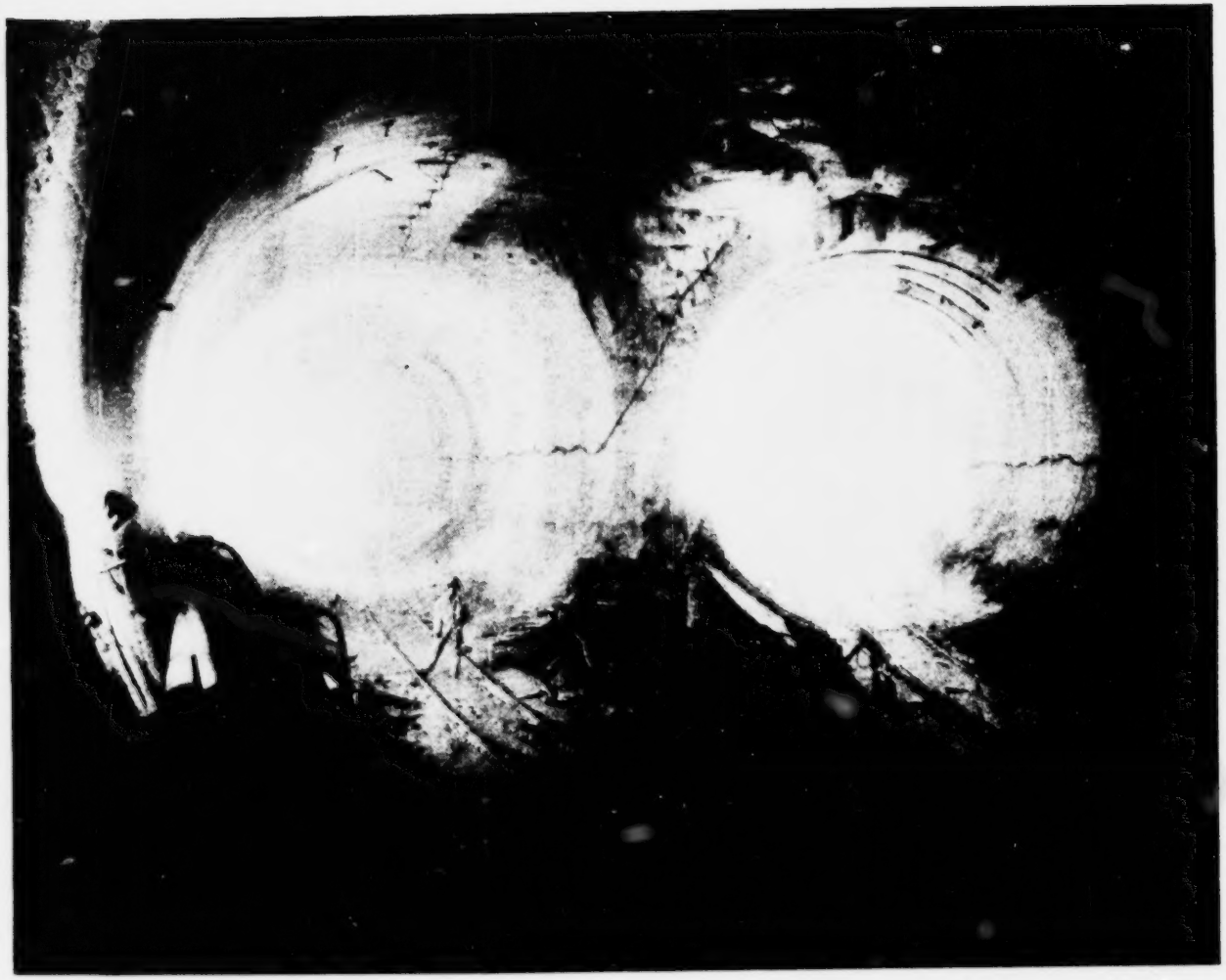

PLATE IV

9.8 METRE WYE TUNNEL BORED BY JARVA TBM:
. note the wall surface in the bore

The predominant factor in the technology is the cutter type and configuration. In this area, the Robbins Company has established a proprietary dominance, with specialty cutter suppliers like Hughes Tool also maintaining a significant market position.

There is little to distinguish the machine concepts with the notable exception of the Atlas Copco machine based on the original Habegger development. (This will be discussed further in Section 2.) The most important factors in commercial success are proven reliability and experience of a wide range of rock conditions. As a consequence of this fact, the Robbins Company has a significant dominance which is being continually reinforced by their extensive and systematic R&D.

Rock tunnelling development in the United States has received a tremendous boost from the MX missile deployment study program. Very large funding has enabled the construction and testing of high-rate tunnelling machines. Dramatic performance has been achieved in medium-strength sandstone where rates up to 15 metres/hour have been consistently achieved.

The Colorado School of Mines (CSM) is the major centre for cutter technology development and machine testing. CSM has a test stand which allows multi-degree-of-freedom tests of a simulated TBM head in a fully instrumented fixture which can accommodate any type of rock. Data are being generated by this facility at a rate unprecedented in TBM development. It has the capability to evaluate optimum operating parameters for virtually any TBM operation.

1.3.2 Water-Jet-Assisted Cutting

CSM and the Bergbau-Forschung GmbH (FRG) are unique in the fact that they have tested TBMs in conjunction with water-jet-assisted cutting.

CSM tests were conducted in a granite quarry near Skykomish, Washington, in 1975. Bergbau-Forschung conducted tests in 1978 in the Federal Republic of Germany.

Both tests were originally conceived to demonstrate actual rock cutting by very-high-pressure water jets. The concept was designed to reduce

the cutting load on the TBM cutter by grooving (kerfing) the rock ahead of the cutters. In both cases the kerfing was found to be problematic. It required a very-high-pressure water supply (40,000-60,000 psi) which created safety and reliability concerns. The energy requirement was also significant (1,000 hp pump capacity versus 150 hp TBM).

However, it was observed that the cooling, cleaning and lubricating action of moderate pressure jets (6,000 psi) directed at the cutters and face produced a large reduction in the torque and thrust required for a given penetration rate. The performance improvement ranged from 50 to 100 per cent penetration rate increase at machine power ratings 30 to 50 per cent lower than dry cutting. The water-jet pumping power at the lower pressure was typically less than 20 per cent of the required pressure for direct jet cutting of the rock face.

The current understanding of water-jet action is highly empirical and researchers are actively pursuing an understanding of the process. It is clear that major productivity improvements can be achieved at the relatively low pressure level and that machine reliability can be increased. The reliability of the high-pressure pumps has been a concern, as has the survival of high-pressure hoses in the underground environment.

2.0 ASSESSMENT OF TECHNOLOGY OPTIONS

2.1 General

In view of the established history of TBM development, and the successful application to a wide range of rock conditions, it is clear that wider use of TBMs in railway tunnelling will require a major improvement in TBM productivity. The economics of short tunnel excavation are also an important factor since tunnels 1 km, or shorter, will be more numerous than 6 to 10 km projects.

Since TBM technology is widely applicable to mining and non-railway tunnel requirements, the incremental improvements to the basic TBM may be more important in smaller-bore tunnels where the financial risk is considerably lower because the TBM is much less costly.

The following assessment will, therefore, address the technology improvement potential on the broadest application basis. The objective is to efficiently excavate rock. Techniques other than the TBM show promise for cost-effective and reliable tunnelling productivity improvement. It is important to keep the market perspective in mind. The wider the application range of the equipment, the lower the business risk to the developer.

2.2 TBM Development Options

2.2.1 The Disc-Cutter, Circular TBM

The purpose of the TBM is to:

- maintain a series of cutters in contact with the rock face
- provide the required axial force to enable cutter penetration
- produce the torque required to move the cutters across the rock face
- remove the spoil from the work face.

The axial force and the torque are related as follows (ref. Appendix B) in a circular full-face machine:

$$\text{TBM Advance Rate} = f_m \left(\frac{\text{(axial thrust)}}{\text{(TBM diameter)(cutting spacing)}} * \frac{\text{(cutter head speed)}}{\text{(cutter edge angle)}}\right) + f_{rock} \left(\frac{1}{\text{rock strength} * \text{rock structural integrity}}\right)$$

It can be seen from these relationships that the following design trade-offs must be accommodated:

(a) Cutter spacing and cutter edge angle. A sharp-angle cutter will penetrate more deeply; however, the chip formation angle is much smaller, requiring much closer cutter spacing to cover the swept face diameter.

(b) The number of cutters is the inverse of cutter spacing:

(no. of cutters) * (axial force) * K = power requirement

It is clear, therefore, that minimizing the cutter drag, either by reducing the number of cutters or improving the cutting efficiency, is the main area for machine design improvement.

The development of cutter edge steels and composites has been the source of most of the productivity gains in recent years.

Water-jet-assisted cutting, using high-pressure jets to actually kerf the rock, attacks the rock structural integrity and produces stress concentrations which lead to shear failure caused by bending stress on the resultant ridge. Since the compression roller cutter is not designed to optimize bending stresses, it is not surprising that the results obtained by the testing in the United States and the Federal Republic of Germany were highly configuration-specific. In effect, the disc cutter must track the kerf grooves and maximize the bending moment on the rock ridge to have any effect. Since, for economy of high-pressure water supply, the kerf cannot be made wide, the spacing of the kerfs must be very close, necessitating a large number of disc cutters.

These compromises lead to a complex, costly head design and vulnerability to failure of even one cutter disabling the TBM.

The success of the low-pressure water jet tests is attributed to the action of the jets in:

- removing debris from the crushing zone
- enhancing chip formation
- lubricating the cutter.

The observed optimal working range of jet pressure[4] (typically 10,000 to 15,000 psi), and the significant reduction in machine torque required (typically 25 to 40 per cent) confirm the interpretation that the disc cutter efficiency is improved because compressive stress concentration is increased and the cutter rate can be increased without the normal increase in cutter wear rate.

This conclusion is fundamental to the future development options for TBM. The implication is that any approach which relies on kerfing the rock to produce a localized failure will not be particularly effective with the disc-cutter, rotary TBM configuration.

A second implication is that discontinuous processes -- for example, using impact, or percussive, energy transfer -- do not integrate well with the rotary disc cutter. Naturally, it is possible to produce widespread weakening or failure of the rock by blanket application of such means but the efficiency of the disc cutter becomes less relevant under such an approach.

2.2.2 The Drag-Bit, Milling Cutter TBM (Habegger-type)

As previously noted, these machines require significantly lower torque and axial force due to the milling action of the heads. The cycloidal motion of the heads (the effect of the contra-rotation of cutting heads and full head) in fact produces kerfs which are sheared by the succeeding head. The success of this design confirms the desirability of the kerfing approach, provided it can be achieved at acceptable levels of cost and reliability. Reductions of 40 per cent in axial thrust have been noted compared to disc cutter circular TBM types.

The Habegger design, therefore, appears to lend itself to the incorporation of means to kerf the rock independent of the cutting heads which then become, effectively, simple milling cutters. Since any cutting device can benefit from lubrication and cooling, the low-pressure water jet should also be beneficial as a means of flushing the cutting zone.

Because the milling-cutter type of head is not restricted to a circular TBM configuration, this option offers significant freedom in applying means of kerfing the rock.

This is the basic rationale in selecting this option for more detailed examination in Appendix C.

2.3 Non-Contact Techniques for Inducing Localized Rock Failure

There are two basic approaches:

(a) localized compressive stress causing crack formation and propagation, leading to chip formation

(b) creation of weakened zones by kerfing so that shear failure can be efficiently produced.

Both of these approaches imply subsidiary mechanical removal of the rock. The only case where pure non-contact erosion is effective is in soft sedimentary rocks which can be "hydraulically" mined. Certain types of chalk and sandstone are mined in this way.

2.3.1 Percussive Methods

Several techniques which cause local structural failure of the rock by impact methods are feasible.

(a) Projectiles (ref. Appendix A)

In theory it is possible to fire small projectiles at a rock face, machine-gun style. In practice, this is costly and logistically impractical, and is not pursued in this assessment.

(b) Water-Cannon Pulsed-Jet Operation

Pulsed water jets have been used for many years in the mining of soft materials. The requirements in hard rock imply very high pulse pressures (50,000 to 60,000 psi) and significant shot volume.

This is not as difficult a proposition as the use of continuous jets at high pressure, since the flow rates are much lower, hence the power demand is also reasonable (perhaps as low as 10 per cent of continuous operation).

Very-high-pressure pulsed jets are particularly effective in exploiting indigenous crack formations in the rock.

This technique can be combined with a conventional impact drill. The mechanical integration of the technologies is reasonably easy. The flexibility and low cost of impact roadheaders makes this a commercially attractive option with a wide application potential. It has been selected as an option for further consideration in Appendix C.

2.3.2 Kerfing

The use of water jets to create kerfs has been discussed in Paragraphs 1.3.2 and 2.2.2.

There are two technologies which are currently being assessed for application to either TBMs or direct-acting cutting devices:

(a) high-power laser

(b) high-pressure water jets:
- without additives
- with abrasive additives
- with viscosity-enhancing polymers.

2.3.2.1 High-Power Laser

Lasers are in wide use for cutting high strength of abrasive materials, for example:

- composites
- ceramics
- super-hard steels.

In these non-mining applications, the laser is usually cutting, or shaping, relatively thin sections. The energy levels are reasonably high, but the power levels are low due to the precise focussing and control of the beam.

In cutting rock, however, there are difficult thermal conditions which require high, continuous power:

- heat transfer to the adjacent rock in three dimensions
- elimination of the molten slag rock which will cause difficulty in shearing the rock between the kerfs if

not expelled from the kerf. Since the molten rock in the kerf cools rapidly, it is a very difficult problem to ensure excavation of the kerf.

The capability of the CO_2 laser to cut rock has been quoted as follows:

Power	Rate
25 kW	25 cm depth at 75 cm/min.
250 kW	50 cm depth at 100 cm/min.

These are unsubstantiated claims. A CO_2 laser has been demonstrated cutting 2 cm thick slabs at about a 10 kW power level. It is extremely difficult to imagine a 25 cm depth cut which can be effectively cleared out prior to re-solidification.

There is no particular benefit to the use of deep kerf cutting in tunnelling. It would be virtually impossible to shear the residual rock shoulders.

A serious problem in the use of the laser is the liberation of gases by decomposition of the molten slag.

The logistics of laser operation in the underground environment are questionable. The beam must be directed through a series of mirrors to the working face. The cleanliness of the mirrors is critical. The transmission path in air must be protected from dust and smoke which would disperse the beam.

Because the laser is only about 10 per cent efficient, the electrical power demand will be very large and the waste heat will create a major ventilation requirement. The laser must be located within a few metres of the working face, and the volume of the laser is a significant space problem. A 40 kW continuous CO_2 laser has been estimated to be about 1.5 metres in diameter; 4.0 metres long; plus cooling equipment and high-voltage supplies.

The internal purity of the CO_2 must be maintained to enable efficient laser action. Any requirement to perform maintenance in the tunnel would be liable to contaminate the interior of the device.

The laser option for use inside a tunnel environment was not pursued in this assessment. The eventual use of a laser for surface operation is conceivable, but some time removed from the present.

2.3.2.2 High-Pressure Water Jets

As a minimum requirement, it is feasible to cut kerfs in rock using water jet pressures which exceed the compressive strength of the rock. In practice, the erodibility of the rock is a major factor. Some rocks which have high cohesive properties may not be effectively cut in this way.

The erodibility factor is covered in Appendix C.

For cutting very cohesive rock, with low erodibility, it is feasible to add abrasives to the water stream. With abrasives added, it is feasible to cut steel. However, the cost of the abrasives is high and it is unlikely that they would be economical for rock cutting on a large scale.

The addition of polymers to the water enhances the effectiveness of the impact jet technique by increasing the energy in the pulse. Again, although technically feasible, the high consumption of polymer additive is likely to remain uneconomic for bulk use.

Appendix C shows that an abrasive material feed supply of 2 kg/min. is required for realistic cutting rates. The number of nozzle assemblies on a given apparatus is likely to be in the range of 2-4. This implies consumption of 4-10 kg/min. Even assuming some recovery or recirculation of the abrasive slurry, this represents a cost of \$12-\$25/min. at current abrasive prices (assuming the use of SiC or Al_2O_3).

It appears that there may be some opportunity to use the contaminated effluent from the kerf as a raw material source for abrasive slurry. This clearly requires scavenging systems which have an acceptable life under these operating conditions. The development of pumping and circulating systems for abrasively contaminated water is likely to be difficult and costly. The technology was considered for the sake of completeness; however, it has not been recommended for further development at this time in the context of tunnelling.

Abrasive mining of high-grade, high-value ore seams, which are often found in very narrow underground formations, would appear to be the best type of application for this technology. The elimination of non-productive waste material due to the precise erosion of the ore-bearing seam could be highly productive.

2.4 Summary and Conclusions -- Technology Options

The mining environment is hostile and the cost of failures is high. Technology which has a reasonable chance of success in tunnelling operations must be:

- rugged
- easily repaired in situ
- unlikely to generate direct hazard due to a failure
- applicable to a range of geological conditions
- capable of evolutionary implementation
- consistent with operating logistic needs at the face.

In this evaluation, two options have been identified as meeting these criteria while offering a significant probability of successful application development. These are:

(a) the Habegger-type milling cutter head in conjunction with high-pressure water-jet assist

(b) the impact-breaker with impulsive high-pressure water-jet assist.

The significant economic factor which discourages wider TBM use is the mobilization cost (ref. Appendix E, Table E.1). In most cases mobilization is a process of blasting a lead-in tunnel to accommodate the TBM, which of course requires reaction surfaces to establish thrust and torque at the cutting face.

A variant of the conventional TBM called a "reaming machine" was used by the Swiss (1969-1973) to bore the Sonnenberg road tunnels (1,400 m). The actual machine, produced by Wirth Co., was a combination of a small-diameter TBM and a two-stage follower system which used the pilot tunnel created by the small TBM to position the large diameter reamers which trailed the TBM. The concept, as demonstrated in the Sonnenberg tunnels, was not so much a discrete machine, as it

TABLE 2.1

OPTIONS EVALUATED FOR FURTHER DEVELOPMENT

Option	Verdict	Reasons for Decision
Circular TBM disc-cutter with water-jet assist	Already developed	(1) Technology is established. (2) Requires only production design based on identified market need.
Continuous high-pressure water-jet systems greater than 20 kpsi	Unsuitable	(1) Energy requirements problematic. (2) Safety hazard. (3) Reliability problems due to stress levels in intensifiers.
Laser-assisted boring systems	Unsuitable	(1) Power efficiency low. (2) Operational feasibility in underground environment improbable. (3) Fundamental difficulty with slag removal.
Habegger-type cutter with:	High potential efficiency	
(a) low-pressure water-jet assist		(1) Basic mechanical cutting technique proven effective. (2) Low-pressure cutting face lubrication applicable and beneficial. (3) Not limited to a full-face circular machine.
(b) high-pressure kerfing assist		(4) This cutter configuration can take advantage of kerfing. Majority of rock conditions can be addressed by 20 kpsi jets.
Impact breaker with impulsive high-pressure water-jet assist	High potential efficiency	(1) Impact breaker is easily mounted and manoeuvred in tunnel. (2) Breaker tool efficiently contains the high-pressure jet. (3) Percussive attack on rock face appears to integrate well with the high-pressure impulse jet. (4) High-pressure supply can be contained. Volume for pulse is acceptable.
Reamer TBM with Habegger-type cutter	High potential flexibility	(1) Provides simplified start-up logistics. (2) Variable finished diameter possible. (3) Easier integration of water-jet assist.

was a series of machines mechanically linked. The reaming machine concept is intriguing because it offers several potential advantages:

(a) The alignment of the tunnel is easier to control with a small pilot TBM.

(b) The ability to locate and brace the large-diameter reaming stage using the pilot bore as a reaction surface and guide means that the reaming stage can be very simple mechanically.

(c) It is much easier to incorporate the milling cutter type of drag bit head if there is a central structural member around which the cutters can be pivoted. Assymetric loading is easier to handle.

(d) Axial force requirements, which are lower for the drag bit cutting head anyway, can be obtained from pull developed in the pilot bore. The combination of axial force and mechanical pivot from the central structure, without the necessity for trailing jacks to advance the boring machine, provides greater freedom at the cutting face.

(e) By developing the axial force from the pilot bore, the full-diameter bore can be "self-starting," i.e. the need for an extensive pilot tunnel is eliminated. This appears to be the most likely approach to economical short tunnel boring.

(f) The development of this concept could begin with component development of the pilot bore TBM, support structure, and milling-type cutters (with or without water-jet assist). The component approach would be considerably less risky than full machine development of a high axial thrust machine.

(g) The pilot bore module could be standardized and different diameter reaming stages could be used. This would avoid one of the main disadvantages of the full-face TBM -- its unique diameter.

3. DEVELOPMENT AND DEMONSTRATION REQUIREMENTS

3.1 Development Rationale

The number of companies which have retired from the TBM business (Table 1.1) is an indication that the costs and risks of TBM develop-

ment are considerable. In the Canadian context, any development which was not aimed at a broad tunnel market, and capable of successful international sale, would be uneconomic.

The success of current TBMs is due, in large part, to the cutter technology. Further development of cutting tools, with or without water-jet assist, will be heavily dependent on the availability of effective materials and fabrication processes.

The success of the TBM simulator at the Colorado School of Mines confirms that the controlled experimental approach benefits field testing at a later stage. All of the technologies identified for further development in this report can be pursued through a multi-stage laboratory and demonstration program.

Significant developments in Canada in the period 1980-1985 have included:

- high-pressure water pumps and intensifiers
- application of water jets to roadheader equipment
- tunnel-boring machine development for soft rock
- evaluation of extruded tunnel lining concepts.

The Canadian technology base is narrow. Most equipment is developed off-shore. The Donkin-Morian mine was an exceptional case where a long access tunnel requirement justified the investment in TBM design and procurement.

There is a definite requirement for a new class of tunnelling equipment, different in form from the current TBM concepts, and capable of rapid mobilization. Since most tunnels required in the railway application will be relatively short, there is a potential trade-off between operating cost and mobilization cost, especially if the availability in situ of the TBM can be high.

3.2 The Development Strategy

The tunnelling environment is demanding and the cost of failure is frequently catastrophic to the contractor. New technology will not be accepted on an unproven basis. Demonstration projects are a necessity.

The Donkin-Morian TBM was developed as a result of pilot tests using a smaller machine. It is clear that "scaling-up" is feasible.

Fortunately, most of the technologies identified as having development potential in this study can be evaluated on a smaller-scale basis. The original intent was to identify full-scale pilot projects. This is not a viable step at this time in the light of the cost analysis results.

3.2.1 Cutter Development

Cutters are presently fabricated by welding high-strength hardened material to a structural support of lower hardness material. This introduces stress concentration problems in both the fabrication and operational conditions. Any cutter design which avoids welding of dissimilar materials, and the necessity to fabricate very tough, hard steels, has the potential for lower production costs.

Two processes, now in wide use, offer an interesting option for cutter fabrication:

(a) Hot Isostatic Pressing (HIP), in which a high temperature and pressure is used to achieve the desired metallurgical properties in a parent material.

(b) Gaseous diffusion (which could also be combined with HIP), in which alloying elements are diffused into the parent material under high pressure at elevated temperature.

3.2.2 High-Pressure Water-Jet Cutting

The nature of the Canadian geology means that conventional metallic cutters are operating near the limit of the materials. Although the reliability of water-jet equipment is uncertain at this time, there is no doubt that the extension of cutter life, increased cutting efficiency and the improvement in the environment at the face are significant benefits. Machine suppliers are generally active in this field.

The development requirements include:

(a) improvements in nozzle life

(b) water filtration systems which minimize routine maintenance

(c) creation of a data base of cutting parameters for a wide variety of rock types and structures

(d) investigation of the performance of drag-bit cutters with water-jet assistance.

3.2.3 Milling-Cutter Head Development

The milling-cutter head integrates very well with the reaming machine concept. It also has good potential application for small-scale rock-cutting projects which are required for tunnel improvements and open cut modifications. Its advantages are related mainly to the reduction in axial thrust required, which implies that portable, or at least easily mobilized, rock-tunnelling equipment could be configured using this type of cutting machinery.

The original Habegger design was discontinued because of higher cost. In a full-face TBM it is clearly a more complex arrangement; therefore cost and reliability are likely to be adversely affected.

In a reaming configuration, the milling-cutter head integrates very well. It is fully accessible, does not require high axial force, and can accommodate variable rock conditions. It can also be arranged to cut non-circular tunnel cross-sections.

Milling-cutter configuration development was discontinued before the current interest in water-jet-assisted cutting. The success of road-headers using water jets implies that the drag-bit cutter is effective in this configuration. For similar historical reasons, the milling-cutter head has not been evaluated with water-jet kerfing of the rock. The potential reduction in machine size, cost and mobilization appears to warrant a systematic investigation -- which could be done very effectively at the component level.

3.3 Recommended R&D Program

The program plan is shown in Figure 3.1. The significant features are:

(a) evaluation of components

(b) synthesis of machine configuration

(c) pilot testing using prototype components

(d) analysis and costing of full-scale machines.

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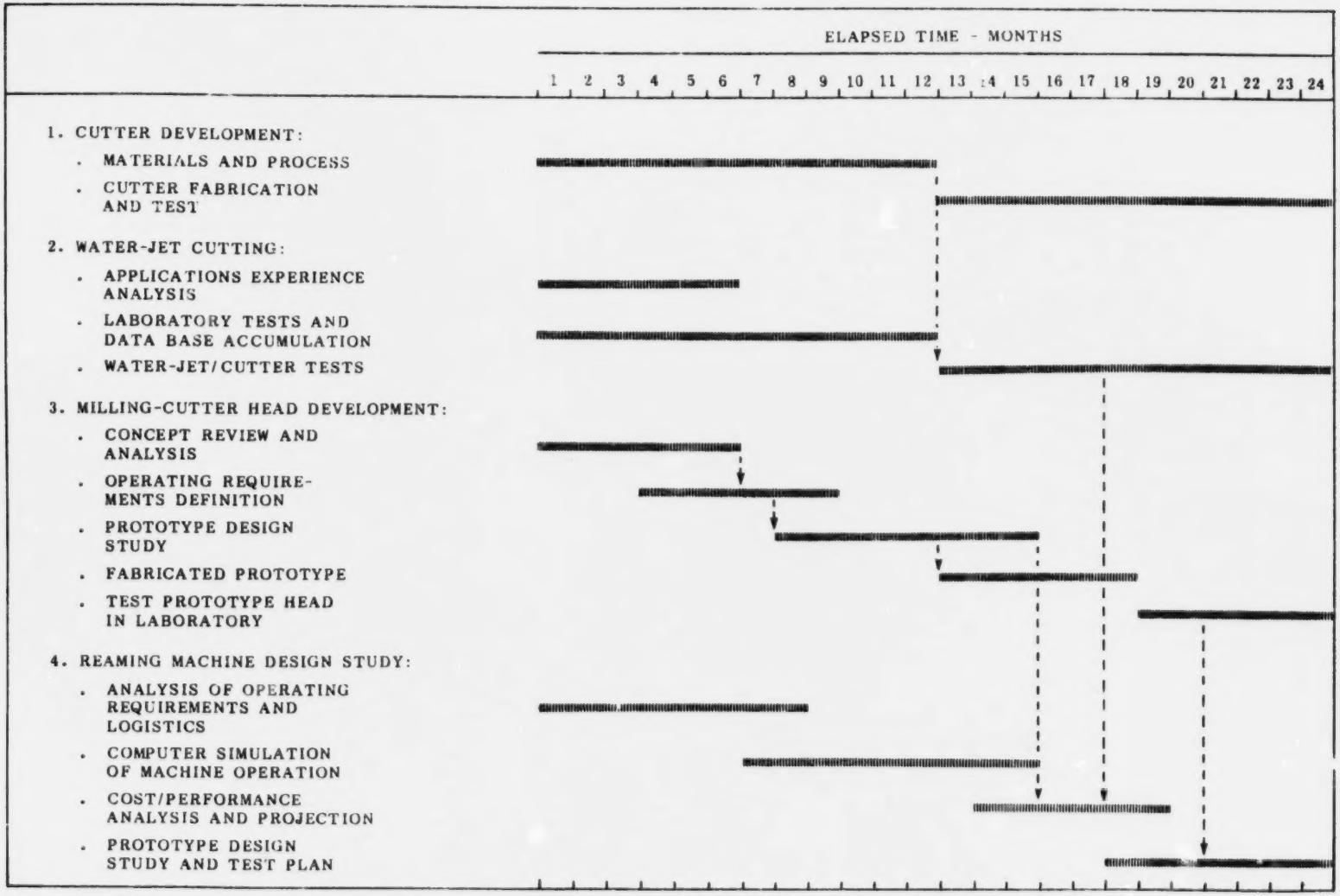
ELAPSED TIME - MONTHS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
1. CUTTER DEVELOPMENT:
. MATERIALS AND PROCESS
. CUTTER FABRICATION AND TEST
2. WATER-JET CUTTING:
. APPLICATIONS EXPERIENCE ANALYSIS
. LABORATORY TESTS AND DATA BASE ACCUMULATION
. WATER-JET/CUTTER TESTS
3. MILLING-CUTTER HEAD DEVELOPMENT:
. CONCEPT REVIEW AND ANALYSIS
. OPERATING REQUIREMENTS DEFINITION
. PROTOTYPE DESIGN STUDY
. FABRICATED PROTOTYPE
. TEST PROTOTYPE HEAD IN LABORATORY
4. REAMING MACHINE DESIGN STUDY:
. ANALYSIS OF OPERATING REQUIREMENTS AND LOGISTICS
. COMPUTER SIMULATION OF MACHINE OPERATION
. COST/PERFORMANCE ANALYSIS AND PROJECTION
. PROTOTYPE DESIGN STUDY AND TEST PLAN

Figure 3.1 Recommended R&D program

APPENDIX A

TUNNEL BORING IN ROCK

Dr. J.H. Curran
Associate Professor
Department of Civil Engineering
University of Toronto
Toronto, Ontario
M5S 1A4

A.1 POTENTIAL HARD ROCK TUNNELLING TECHNIQUES A.1
A.1.1 Drill and Blast A.1
A.1.2 Tunnel Boring Machines A.1
A.1.3 Water Jet Fragmentation A.2
A.1.4 Thermal Fragmentation A.3
A.1.5 Large Impact Hammer A.6
A.1.6 High-Velocity Projectile Impact A.6

It has been recognized for some time that major changes in tunnelling methods will be required in the near future. This appendix outlines some of the new methods which are being considered for driving tunnels in hard rock.

A.1 POTENTIAL HARD ROCK TUNNELLING TECHNIQUES

A.1.1 Drill and Blast (Conventional)

Drill and blast is the only method in widespread use for tunnelling in hard rock. As a result of the blast, a (tensile) shock is propagated through the rock mass, causing the rock to fracture. Blasting is effective because it efficiently exploits the weakness characteristics of rock. This method is applicable to any size and shape of opening.

The drill and blast method is highly developed from both a theoretical and practical point of view. Techniques for producing openings with a specified geometry are in widespread use (e.g. presplitting). The major problem is controlling overbreak.

A.1.2 Tunnel Boring Machines

Mechanical boring machines are capable of driving tunnels economically at continuous high advance rates in soft to medium-hard rock. In hard rock, however, cutter wear is usually very heavy due to the limitations of the material presently available for their manufacture. This results in a slower penetration rate, increased machine downtime, lower tunnelling rates and higher costs.

Drag-bit and roller-cutter full-face boring machines, although giving reasonable values of specific energy, require massive structures for the application of the very high thrust forces needed to force the cutters into the rock. Weight and size of these machines consequently are too great for the operating flexibility required from a stoping machine. These machines are further limited for mining purposes in that they cannot take advantage of natural weaknesses in the rock but attack the face in a fixed, repetitive pattern. Tool wear is aggravated because the cutting mechanism is such that large cracks are not propagated through the rock and the muck is produced in relatively small chips.

The majority of TBMs on the market today use "brute force" to break the rock. A major part of the cost of a TBM goes to producing the high axial force and torque necessary to fail the rock at the tunnel face.

Much research remains to be done to optimize the design and placement of the cutters. At present, TBMs are limited to circular tunnels.

A.1.3 Water Jet Fragmentation

Water jet systems may be continuous or pulsed (water cannon). They can break any type of rock. They can be powered electrically and will not pollute the underground atmospheric environment. The specific energy for rock breakage can be comparable to or lower than for present rolling cutter bits. They do not require high axial forces to be applied to the rock face by the tunnelling machine. They generate high noise levels, unless properly muffled. Water disposal becomes a problem for continuous water jets.

The major problems with the continuous high-pressure systems are the reliability and life of seals and check valves. In addition, the use of continuous pumping systems for tunnelling will generally require reliable high-pressure rotary seals or flexible seals to permit jet nozzles to transverse the rock face.

In designing a TBM with water-jet assist, some of the key variables to be considered are: water-jet pressure, nozzle size, standoff distance, speed of traversal of the jet, and multiple passes in the same slot.

A very significant reduction in required torque at all penetration rates is observed when water jets are used in combination with a TBM.

One of the most promising methods is to use water jets to cut slots in the rock and then to break the material between adjacent slots by mechanical tools such as rolling disc or gear cutters.

Effectiveness of water-jet cutting increases with jet diameter but large-diameter jets must operate on a pulsed basis because of excessive power requirements for continuous operation.

A major problem is to identify the rock properties which control the erosion and breakage process.

As compared to a continuous jet system, a pulsed jet system with the same average input power can produce jets of larger diameter and therefore greater range of effectiveness.

Jet pressure of a water cannon should be at least ten times the compressive strength of the rock.

Research is needed to determine the endurance (particularly the cyclic fatigue life) of nozzles because the nozzle replacement cost should be less than the cost of rolling cutter bits when used against similar rock.

Additional problems to overcome are water supply and recovery, control of humidity, visibility at the face, protection from flying rock fragments, and minimization of overbreak at the tunnel wall.

A.1.4 Thermal Fragmentation

One of the most important advantages of many heating techniques is the lack of direct contact between the heating device and the rock. This means a lower wear rate relative to mechanical cutters, and no large reactant force to be supplied by the tunnelling machine. In addition to avoiding physical contact, some heating systems (e.g. electron-beam guns and lasers) can deliver energy to a rock face much more intensely than can be conveniently handled mechanically. Thus, heating power densities of the order of 106 to 107 watts/in.^{2} and greater can be achieved with high-power lasers. These high-power levels allow much higher instantaneous penetration rates than can be achieved by mechanical cutting.

Another advantage that accrues to some thermal techniques, such as, for example, surface spalling, is that the thermal fracture process works particularly well in certain rock types (e.g. granite) that are very hard to cut mechanically. Other methods, involving high power density, are able to cut any rock type, and are relatively unaffected by the rock hardness or strength. Therefore, thermal methods are at present employed for some hard rock situations where no other controlled method of excavation is available.

Generally speaking, many of these thermal methods are being thought of as auxiliary weakening or fracture devices which, when added to mechanical tunnel-boring machines, may extend the boring capability of these machines to very hard rock.

Although there are some schemes whereby the entire removal process is performed by thermal energy, these will require substantially greater development.

In general, thermal rock fracture techniques can be divided into five modes.

Surface Spalling. This fracture mode consists of fragmentation of a rock body near the surface due to thermal stresses induced by surface heating. Efficient spalling requires a heating stream with some kinetic energy also to remove the spalled particles, which are not necessarily removed from the surface by heating alone. Thus, jet systems burning fuel and air or oxygen are usually employed for efficient spallation. Rocks which spall best are those in which a very high thermal gradient can be developed near the surface but more research is required to predict the "spallability" of rock.

Internal Heating. In this mode of fracture, failure is induced in the rock by thermal stresses caused by the release of heat below the surface of the rock. As in surface spalling, maximum temperatures are well below the rock melting temperature. However, the response of specific test rock types to surface spalling has been shown to be different than their response to fracture by internal heating.

Unfortunately, the RF field does not always heat the rock efficiently. Thus, the technique is probably not well-suited to a tunnelling situation, in which a wide variety of rock types are encountered.

Heat Weakening. Heat weakening refers to the degradation of rock material strength by the application of heat. The weakening of the bulk strength properties of rocks is due to an increase in the micocrack structure of the rock by heating. This phenomenon may be distinguished from surface spalling in that rock is not necessarily broken apart in the weakening process. Also, it is presumed that any rock

type would be susceptible to some heat-weakening given sufficient heat input energy, whereas certain rock types will not exhibit surface spallation.

Efficient heat-weakening involves long-time heating of the rock surface without causing melting, so that a large fraction of the input heat is transmitted deep into the rock mass. The employment of a low heat flux to increase the efficiency of heat-weakening may incur a peripheral problem of an uneconomic reduction in the overall tunnelling rate to allow the long heat-soaking time.

Bulk Rock Melting. This category includes results where melting of the rock occurs due to the application of power densities of less than about 1 kW/cm^2 to the rock face. In general, this would apply to concepts employing bulk melting of rock by use of such tools as electrically-heated mechanical elements. The heating elements used in this mode would have effective maximum temperatures of about 500° Celsius.

Selective Rock Melting (high power density). The use of very high power density, such as achievable with electron-beam guns and lasers, allows very rapid penetration of rock (order of centimetres per second) with effective stagnation temperatures greater than the vaporization temperature of rock. In addition, these highly concentrated heating tools allow selective, thin melt cuts or holes to be made, so that only a small amount of the total rock fractured is melted or vaporized. Tests made with these kinds of devices are made with the heating beam stationary (hole-drilling) or moving across the rock face (kerfing).

The possibility of making holes or thin melt cuts in rocks with lasers or electron beams may be useful for tunnelling in several ways. One possibility is that selective cuts may be made at troublesome areas of the tunnel face, such as at the gauge. Such a cut accounts for a large part of the downtime and cutter cost in mechanical tunnelling operations. Another possibility is to cut sequential kerfs or holes in the specific patterns, so as to fracture large chunks of rock from between the kerfs.

A.1.5 Large Impact Hammer

Mechanical fragmentation methods generally have specific energies much lower than that of more novel methods. Impact breaking has an efficiency exceeded only by that of drill and blast methods. Mechanical impact has another advantage over most other methods of fragmentation in that it is applicable to almost all types of rock. Other methods may require some property such as thermal conductivity or dielectric strength to fall within a narrow range of values for the process to work well, but this is not the case for impact breaking. Success has been achieved in rocks ranging from the hardest quartzites to soft sandstones and conglomerates.

An additional feature of impact machines which makes them attractive for mining compared to other mechanical systems is their ability to function without high thrust forces. Impact breakers, in contrast to TBMs, are carried on light structures, give excellent access to the face for mucking, permit the operator to exploit planes of weakness in the rock, allow visual inspection of the cutting tool during operation, can follow an irregular ore body, and yield lower specific energy.

At present, impact hammers are used primarily for the secondary breaking of rock.

A.1.6 High-Velocity Projectile Impact

This technique consists of firing projectiles (e.g. concrete or steel cylinders) at the rock face using large military-type guns. Impact velocities of 5,000 fps are typical and pressures of about 2 million psi are generated over a period of microseconds. This fragments the rock by a complex combination of crushing, fracturing, and spalling. In tunnelling, full advantage is taken of prefracturing and crater interaction by careful placement of successive shots, similar to the sequencing of holes in a drill and blast round. Proponents of this method claim advance rates from three to seven times faster than drill and blast, at less than two-thirds the cost.

Major problems are with controlling excessive noise levels, flying rock fragments, and minimizing overbreak.

APPENDIX B

APPLICATION OF HIGH-PRESSURE WATER JETS IN TUNNEL BORING

Dr. J.H. Curran
Associate Professor
Department of Civil Engineering
University of Toronto
Toronto, Ontario
M5S 1A4

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B.1 INTRODUCTION

This appendix focusses on the use of high-pressure water jets which hold considerable promise for significantly improving the applicability and economics of mechanical excavation in rock.

B.2 TUNNEL-BORING MACHINES

At present the two major methods of tunnelling in rock are tunnel-boring machines and conventional drill-and-blast. Full-face tunnel borers have been used around the world since the late 1950s and experimentally since one-hundred years earlier. In the past ten years there have been great improvements in the capability to bore in the hardest rock types.

During this time, conventional drill-and-blast tunnelling has also progressed and presents a continually improving standard for those working on the development of mechanical excavation systems. However, the number of skilled miners available today to carry out the specialized tasks needed for drill-and-blast excavation has been gradually declining. Also, the speed and cost advantages of conventional tunnelling and mine development have narrowed and in some cases disappeared even in the hardest rock types.

A conventional tunnel-boring machine consists of a heavy frame and a rotary head studded with disc cutters. Hydraulic rams brace the frame against the tunnel wall and thrust the cutter head against the tunnel face. The disc cutters grind the face into chips several centimetres across. After the tunnel has been advanced approximately a metre, the cutter head stops and hydraulic rams draw the frame forward for another stroke.

Rock cutting requires energy to overcome cohesive forces within the material. Contact forces across grain boundaries maintain cohesion, so the required energy is proportional to the grain surface energy created during disintegration. The larger the chips broken out of a tunnel face, the lower the power requirement will be to drive the tunnel.

When cutting rock, the discs penetrate a depth, h_d, equal to the advance per revolution of the tunnel-boring machine. A distance, r_k, separates adjacent kerfs, and r_k must be small enough that a single disc passage splits out the material between the kerfs. Disc cutters owe their efficiency to the fact that they form pancake-shaped chips, with lateral dimensions, r_k, much larger than their thickness, h_d. One of the arts of tunnelling machine design is to choose the ratio h_d/r_k as small as possible, consistent with complete breakage.

Aside from the question of ground stability and support, the most important economic factors in machine tunnelling in hard rock are penetration rate and cutter costs. Cutters usually wear out, although in hard, blocky ground some are simply smashed by the tremendous impact loads of the boring operation. The rate of wear and replacement is important because it determines both the cost of the cutter parts consumed in boring the rock and the amount of down time for cutter changing.

Wear rate is basically a function of the abrasive characteristics of the rock. Penetration rate is a function of the cutter geometry, thrust of the machine, and the rock strength.

The relationship of these elements can be expressed as follows:[4]

(a) cutter costs per linear metre of tunnel:

$$\text{cost} = f_1 \frac{(\text{diameter})^2}{\text{thurst per cutter}} + f_2 \frac{(\text{rock strength})(\text{abrasiveness})}{\text{intensity of jointing}}$$

(b) penetration rate per minute of boring time:

$$\text{rate} = f_3 \frac{(\text{machine thrust})}{(\text{diameter})(\text{cutter spacing})} * \frac{(\text{cutter head speed})}{(\text{cutter edge angle})} + \frac{\text{intensity of joints}}{\text{rock strength}}$$

One can conclude from the above relationships that as mechanical tunnelling has moved into harder rock, it has been necessary to increase the thrust per cutter and reduce the cutter spacing, resulting

in greatly increased total machine thrust. Consequently, this has increased the other machine specifications, such as power and structural, mechanical and hydraulic capacity.

Steady technological advances in cutter strengths and wear rates have occurred over the last ten years and it is presently possible to bore in very hard rocks (in excess of 350 MPa compressive strength) using large-diameter tunnel-boring machines.

However, except for machines designed for a long tunnel (e.g. greater than 10 km from one point to another), these heavy, expensive machines will never satisfy the majority of the needs and requirements for underground excavation.

There is a need for improving the efficiency of mechanical cutting disc drill tools by means of reducing the feed forces required to break the rock, making possible lighter and more flexible designs of full-face equipment for tunnelling. The present application range of the technology of tunnel-boring machines in hard rock of 5 to 10 per cent could thus be adequately broadened and shorter driving lengths (e.g. 1 to 2 km) could be economically produced by fully mechanized equipment.

B.3 HIGH-PRESSURE WATER JETS

One of the most promising methods of more efficient rock breaking is a combination of cutting discs and high-pressure water jets.[2] The important feature is to combine an efficient cutting tool[1] (i.e. the high-pressure water jet) with an equally efficient breaking tool like cutting discs. The water jets, situated on either side of the drilling tool, cut grooves and the rib left in between is removed by the shearing action of the cutting discs (Figure B.1). With the water jets present, the load exerted on the rock is very different (sharing action) from the forces acting on the rock with purely mechanical breaking (pressing/squeezing action). The result is that the static forces required for the functioning of the cutting discs can be reduced in proportion to the compressive/tensile strength ratio of the rock.

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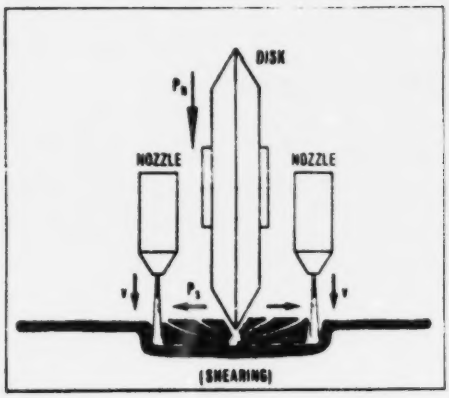
1 A water jet can also fracture rock in planes of high permeability, but more typically a high-speed water jet erodes a neatly defined slot.



(from ref. 3)

Figure 1 Principle of water-jet-assisted boring

The high cutting efficiency of a high-pressure water jet is attributable to the energy transfer via an extremely small contact face between the water jet and the rock surface; this contact face corresponds to the cross-section of the water jet. Therefore, the cutting efficiency of a water jet is typically found to be greater than that of cutting discs by a factor of 1,000 to 2,000.

B.3.1 Laboratory and Field Tests

Over the last decade, two major laboratory/field studies have been conducted on the concept of combining high-pressure water jets with disc cutters on a tunnel-boring machine.

The first major research investigation[2] of the concept was conducted by a team of reserachers from the Excavation Engineering and Earth Mechanics Institute at the Colorado School of Mines, The Robbins Company (manufacturer of the tunnel-boring machine), and Flow Research Inc. (specialists in water-jet technology).[5] The research was financially supported by the National Science Foundation and the U.S. Bureau of Mines.

2 Hereafter referred to as CSM.

The intention of the tests was to show that with the assistance of high-pressure water jets the rate of advance for full-face tunnel borers in very hard and abrasive rock could be increased.

In order to provide the necessary preliminary design parameters for placement of the jets on the boring machine, laboratory tests were conducted to determine what effect key variables would have on kerf formation in the granite formation of the field test. The effects of the following were investigated: water jet pressure, nozzle size, standoff distance, speed of traversal of the jet, and multiple passes in the same slot.

In agreement with other researchers, it was found that there is a critical pressure which must be exceeded to cut the rock effectively (for granite approximately 3,450 bar was found to be the optimum). Nozzle diameter was also observed to affect cutting performance significantly, there being an approximately linear increase in depth of kerf with increasing nozzle diameter. However, since the power required increases with the square of the diameter, increasing nozzle size is not the most effective way to utilize the available water jet power to improve kerf depth. It is desirable for jet performance to maintain the minimum standoff distance because of the tendency of the jet flow to break up at a distance of between 100 and 200 diameters from the nozzle. However, due to the irregularities in any tunnel face, the nozzle holders need to be set back and protected.

By virtue of the design of most full-faced tunnel-boring machines, there occurs a considerable variation of traverse velocity at various distances from the centre of the bore, and for this reason the effects of cutting speed on the performance of a water jet were investigated. Samples from the field site were tested in the laboratory at jet traverse velocities ranging from 1.25 cm/sec. to 100 cm/sec. The results indicated that initially there was a rapid decrease in kerf depth for an increase in traverse speed, and then a much lower rate of decrease for the higher velocities.

The field tests, which were carried out in a granite quarry near Skykomish, Washington, were conducted using a 2.1 m tunnel-boring machine built by The Robbins Co. in 1963, modified to accommodate

various sizes and numbers of water jets. The rock of the test site was a hard, tough granite.

The concept was proven that water jets could be added to a conventional tunnel borer and significantly improve the advance rate. The average increase in the advance rate during field testing was from 50 to 60 per cent. For some tests, advance rates were more than doubled.

An interesting observation made during the field tests was that there was approximately a 25 per cent reduction in the required torque when the water jets were used. It was felt that this was due to reduced friction on the cutter head.

Three different jet patterns were tried, all of which proved effective in assisting mechanical cutting in the laboratory. In the field tests, however, only the configuration of the jets between the cutters was effective. The configurations of jets under the cutters and jets under and between cutters actually reduced machine advance rate.

Various nozzle sizes were also tested in the field. The 0.30 mm nozzle was found to cut the best. Larger sizes were tried but were found to be less effective, possibly due to hydraulic characteristics of the nozzle holders used. Multiple nozzles in a single nozzle holder were tested in the laboratory and to a limited extent in the field. Although cutting deeper than a single nozzle, interference caused by the close proximity of the jets caused the double nozzle to be less effective than two separate passes of a single nozzle in the same slot. Multiple nozzles appear to be a good way to apply larger amounts of power to a particular location, but further studies are needed to determine minimum separation distances between jets of a multiple nozzle and how to design and place this multiple nozzle in a boring machine.

To determine if the improvements offered by water-jet-assisted tunnelling warranted the additional expense of such a system, a comprehensive economic analysis was undertaken. Very significant savings were predicted, depending primarily on the percentage improvement assumed. A minimum increase of approximately 10 per cent was needed, with savings increasing rapidly for greater improvements in advance rate. Levelling off of cost benefits occurred for large increases in

advance rate. Using a 50 per cent increase in advance rate, cost savings of 14 and 26 per cent were projected for 3.04 m and 6.08 m diameter tunnels, respectively. With the optimization of the equipment and machine design, it was felt that even higher increases in advance rate than obtained in the prototype test should be possible, with corresponding increases in cost savings.

The second major investigation[3] of the concept of combining high-pressure water jets with a conventional tunnel-boring machine was conducted in 1979-80 by Bergbau-Forschung (FB), central research institute of the German coal-mining industry, in cooperation with Maschinen-und Bohrgerate Fabrik A Wirth & Co. (manufacturer of the drilling equipment).[3] These full-size tests were carried out on a TB1/260 Wirth tunnelling machine of 2.6 m drilling diameter in a sandstone quarry of the Upper Carboniferous near Dortmund-Hohensyburg, West Germany.

While the purpose of the original tests by CSM was to show that with the aid of water jets, penetration rates of a tunnel borer in very hard rock could be increased, the objective in the BF tests was different.

At present rates of advance of tunnel-boring machines in coal mines, there are already considerable transportation problems, not only for debris disposal, but also for material supply. Further increases in tunnelling speed are of less interest than are the advantages of lighter and more flexible tunnel-boring machines. This decrease in weight and increase in flexibility would lead to a decrease in the pre- and post-investments for their underground installation and operation. Design calculations showed that by applying a more efficient drilling method and thus reducing the required feed by 50 per cent, the weight of full-face tunnelling equipment could be reduced by an approximately equal order of magnitude.

The essential test results are summarized in Figure B.2 where the dependency of the drilling rate on the feed of the drilling head is shown, both for the purely mechanical drilling as well as for the jet-assisted operations. The gap between the curves closes at higher feed

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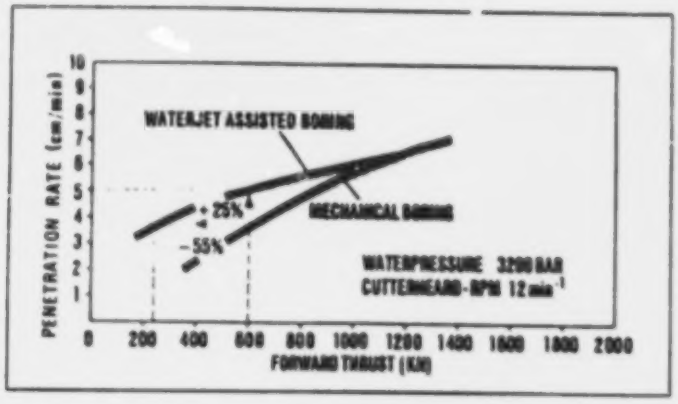
3 Hereafter referred to as BF.

forces according to the drilling speeds. This means that the positive influence of the high-pressure water jets diminishes with both increasing feed forces and drilling speeds and will finally disappear completely.



(from ref. 3)

Figure B.2 Summarized BF test results for purely mechanical and water-jet-assisted tunnel boring

When considering, however, only the lower to medium curve sections, it becomes obvious that the feed of 600 kN applied to the equipment and corresponding to a drilling speed of 3.5 to 4.0 cm/min. could, indeed, be reduced by 55 per cent against purely mechanical drilling as soon as high-pressure water was applied. This beneficial effect is proportional to the installed hydraulic capacity and, in the present case, was obtained with a water volume of 120 litres/min. at a pressure of 3,600 bar.

This is a reconfirmation of the initial hypothesis that the efficiency of the cutting discs of a full-face tunnelling machine can be considerably improved by means of high-pressure water jets. The initial goal was reached in that it was possible to reduce the required feed by more than 50 per cent. This, in turn, would entail proportional decreases in the machinery weight with beneficial effects on the flexibility of such a tunnelling system.

Another test series served to investigate the influence of high-pressure water jets on increasing tunnelling speed. In this series, the feed force rather than tunnelling rate was maintained constant. It was found that at a constant feeding force of 600 kN and at a water pressure of 3,200 bar the drilling speed could be doubled.

B.3.2 Potential and Limitations

When evaluating the potential and limitations of this new technology, it needs to be emphasized that providing high-pressure water at 3,000, up to 4,000, bar for rock breaking is commercially available.

Although the tests by CSM and BF both confirmed the soundness of the idea of combining cutting discs and high-pressure water jets for rock drilling, the relevant energy consumption is still relatively high. For the BF tests, if the 1,000 kW of drive capacity of the high-pressure jet installation is related to the present drilling diameter of 1.6 m, a specific performance of 385 kW/m of drilling diameter results. When extrapolating to the drilling diameter of traditional full-face tunnelling machines as used in hard coal mining, an additional capacity of 2,000 to 2,500 kW would have to be installed. The saving of capacity for the rotational drive of the drilling head, amounting to some 40 per cent or 300 to 400 kW, may be deducted from the above requirement. Similar results were found in the CSM tests.

Apart from the expenditure for the electrical installations[4] for operating this type of high-pressure jet installation underground, potential impacts on the mine climate would be considerable. Whereas the created volume of high-pressure water of 120, up to 240, litres/min. will only increase the water content of the drilling by 5 to 10 per cent, the muck would, however, be heated by the heat generated in rock breaking to a theoretical value of 65° to 80° celsius. As a result, haulage would have to be provided for removing the muck separately from the underground workings, either in special mine cars or by hydrotransport. If not, the mine air temperature can be expected to rise considerably which, in

4 Although electrical requirements may be higher with the use of continuous water jets, electrical costs are not normally a significant factor in the overall tunnelling costs (i.e. typically less than 2 per cent of the cost per metre).

turn, would require adequate cooling installations and, thus, additional technical equipment.

Certain additional improvements can be achieved by optimizing the water-jet/cutting-disc combination. The number and diameter of the nozzles can be varied over a wide range and it is expected that further energy savings can be realized by optimizing their size and distribution.

Another possibility is to optimize the water-jet/cutting-disc system. Experiments have shown that the attainable feed reduction is proportional to the groove depth, h_w, cut by the water jet and inversely to the groove depth, h_d, of the cutting disc tool as well as inversely proportional to the spacing, r_k, between the cutting disc tool and the water jet.

Unfortunately, the relation between the required energy expenditure and the parameters, h_w and r_k, is similar; the relations are inverted merely as far as h_d is concerned. The result of these respective relations is that the feed reduction is proportional to the energy expenditure and inversely proportional to the second power of the penetration depth, h_d, of the cutting disc tools. Thus, there is a need to optimize between the competing objectives of minimum energy expenditure and maximum pentration depth of the cutting disc which is crucial to the drilling advance rate.

A number of investigators have also found that the efficiency of a water jet increases along with rotational speed. Therefore, it is possible that with an increase of rotational speed the feed capacity can be reduced while maintaining the same advance rate. Linear exchange of both parameters is possible up to a certain extent. The evaluation of experimental measurements also shows very clearly that the specific energy expenditure diminishes along with higher rotational speeds of the drilling head.

The above effect should be helpful in optimizing utilization of high-pressure jets on tunnelling machines, the more so as the hazard of spark creation in purely mechanical drilling at high rotational speeds will be eliminated by the utilization of water jets.

Attempts have also been made to improve the efficiency of high-pressure jets by additives such as molecular liquid polymers. Even in low concentrations, they can substantially increase the viscosity of water. In conjunction with a supplementary lubricating effect brought about by the presence of certain hydrocarbon components, the following beneficial effects may be expected: reduction of frictional resistance, increase of flow speed, less wear of the nozzle material, improved energy utilization, and finally a narrower confinement of the water jet. Laboratory investigations on sandstone at pressures up to 2.5 kbar confirmed that by using additives in the pressurized water, either the grooving depth was increased up to 70 per cent or pressure reductions up to 40 per cent were obtained when producing grooves of the previous depth.

The grooving depth desirable for rock breaking by means of cutting discs and water jets can thus be obtained at considerably lower water pressures. This should be particularly relevant for very hard rock such a granite for which higher jet pressures are required.

However, the most promising means of improving the water-jet/cutting-disc combination appears to be to use pulsed rather than continuous water jets.[1] Whereas continuous jets are produced by pumps or pressure intensifiers, pulsed jets are produced by "water cannons" which employ impact of a free piston to extrude water through a nozzle. As compared to a continuous jet system, a pulsed-jet system with the same average input power can produce jets of larger diameter and therefore greater range of effectiveness. Pulsed jets can also reach much higher pressures because they do not require tightly fitting, sliding seals or check valves. They also obviate the need for high-pressure rotary seals which continuous jets need for traversing. Also, because much less water is required to operate pulsed jets, their tendency to heat the mine environment is diminished. The major obstacle in using the pulsed-jet technology, as it is available today, is that its development is still in the relatively early stages.

B.4 CONCLUSIONS

The potential technical advantages of combining high-pressure jets with tunnel-boring machines can be summarized as follows:

- low feed requirement
- less bulky equipment design
- easier mounting and dismantling of equipment
- easier moving of equipment
- reduced drive requirements for the drilling head
- reduced wear at the drilling tools
- more efficient dust suppression
- elimination of sparks
- reduced proportion of smalls in the drilling
- smaller energy requirement when pulsed water jets are used.

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APPENDIX C

SPECIFIC MACHINE CONFIGURATIONS AND OPTIONS IDENTIFIED FOR FUTURE R&D

Dr. R.J. Puchala
Manager of Research
Indescor Hydrodynamics Incorporated

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C.1 CONCEPTUAL CONFIGURATION OF ROCK CUTTERS

Of the many possible configurations and combinations of water jet cutting tools with existing tunnelling machines, three particular scenarios appear at this time to be most promising. It is desired to build a machine that increases productivity, has a high degree of reliability, and is suitable for use in various tunnel geometries. The merits of each option are discussed in terms of these references, with particular regard to good engineering design. This should seek to minimize mechanical complexity and hence the risk of failure, while maintaining the required control over the system.

C.1.1 Combination of Independent Cutting Water Jets and Rotating Discs for Habegger-Type Circular Tunnelling Machine

This concept is shown schematically in Figure C.1. The nozzles are moved in the same plane as the rotating cutters, although the plane of rotation of the discs and the nozzles may be deviated by the angle α. This deviation causes a change in the distance between the nozzles and the rock surface. Consequently, the depth of the kerf (water jet cut) will be different for each jet.

This combination has a number of advantages:

- Nozzles will be supplied with high-pressure water through only one rotating seal, which reduces maintenance problems.
- The position and number of nozzles is readily adjustable. This is convenient for testing and also allows flexibility in adaption to different rock properties.
- Installation of the high-pressure supply line and nozzles is simple.
- There is good access to the high-pressure installation for adjustment and repair
- The cut of the jets is deep due to the slow rotation of the nozzles

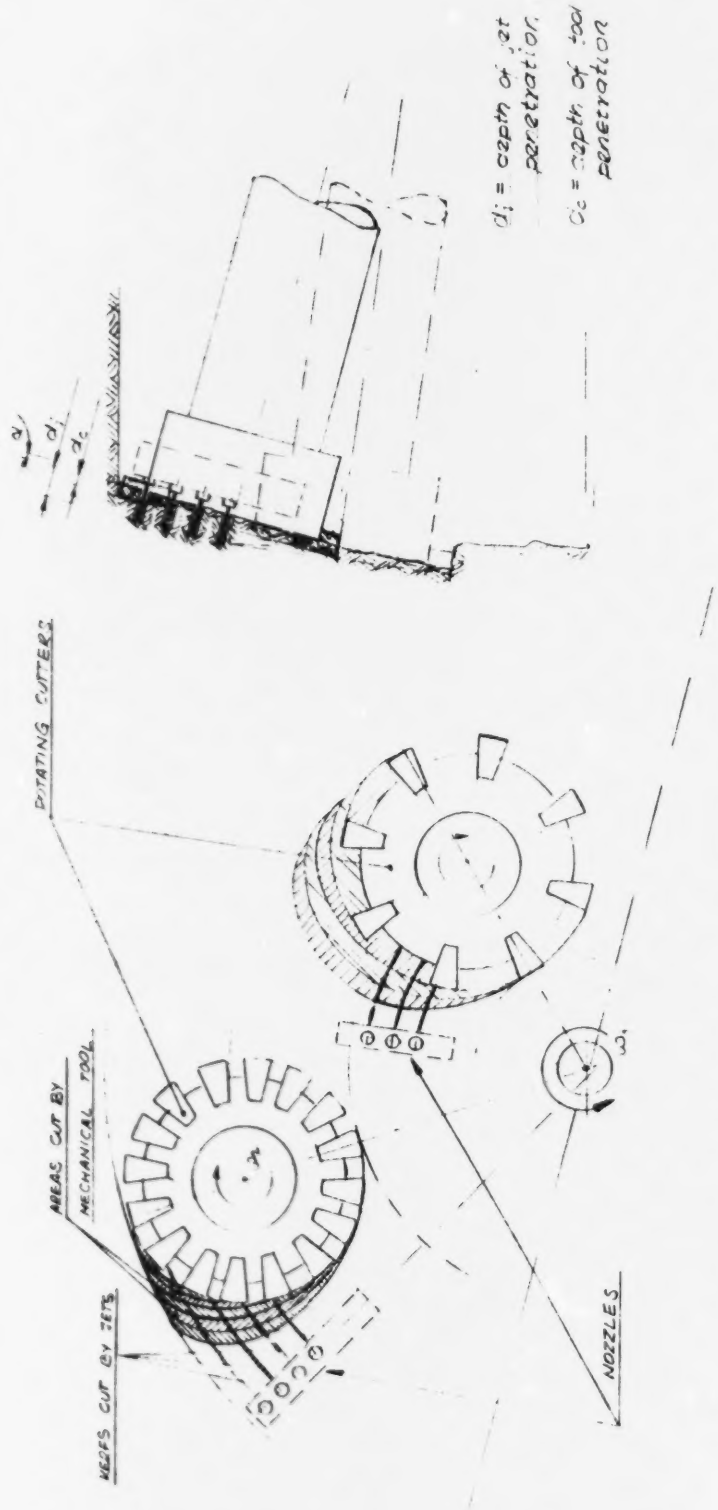
d_j = depth of jet penetration
d_c = depth of tool penetration
ROTATING CUTTERS
AREAS CUT BY MECHANICAL TOOL
REEFS CUT BY JETS
NOZZLES

Figure C.1 Milling-cutter/water-jet configuration

- No energy dispersion of the water jets because contact is maintained with the rock face at all times.

As a result of the kerfs created in the rock, the cutting bit produces a shearing rather than crushing action which chips out the rock. The assumed geometry of the drag bit and cutting force is illustrated in Figure C.2. For a sharp bit, the Nishimatsu relationship is used to calculate the required cutting force per width of tool edge, $\underline{F}$.

$$\underline{F} = \frac{2t}{n+1} \cdot \tau_o \cdot \frac{\cos \phi}{1 - \sin (\phi - \alpha + \psi)} \qquad (1)$$

where: τ_o = cohesive strength of the rock

ϕ = angle of internal friction of the rock

t = depth of cut

α = bit rake angle

ψ = angle between the direction of the resultant cutting force and the normal to the rate face of the cutting tool

n = stress distribution factor.

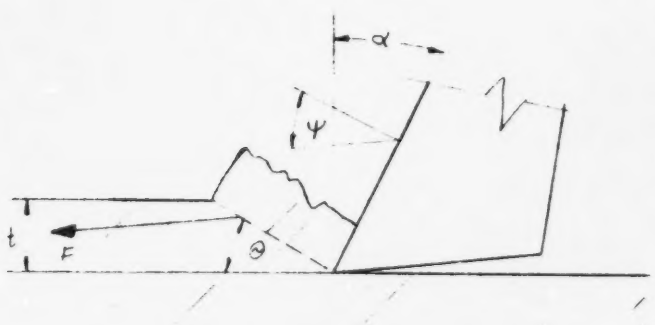

Figure C.2 Geometry of drag bit and cutting force

It is quite likely that equation (1) may also be employed to calculate the cutting force required for a drag bit with water-jet assistance. The geometry of such a configuration appears in Figure C.3. The shape

and dimensions of the areas which are sheared during this hybrid cutting action will change frequently as a result of the suggested kinematics of the cutting tools and water jets. Slots (kerfs) created ahead of the cutters definitely improve the stress distribution factor, n, so that the cutting force, F, will be lower than that required for purely mechanical cutting activity.

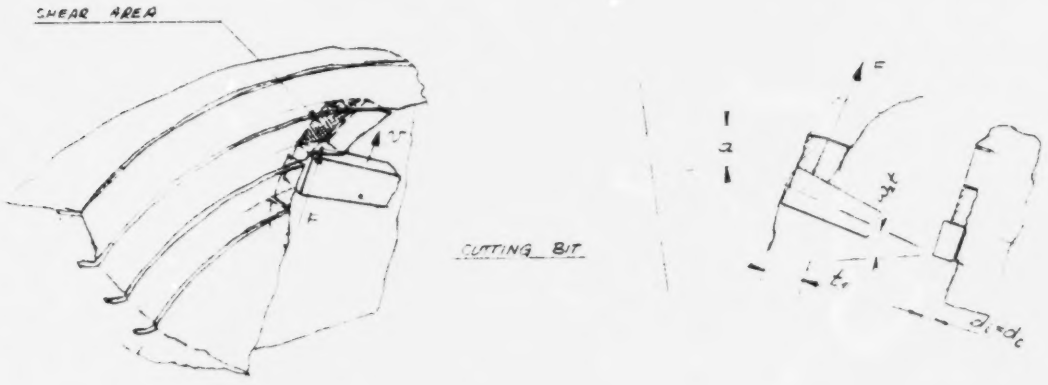

Figure C.3 Geometry of drag bit with water-jet assistance

Some experiments with water-jet-assisted drag-bit cutting have been reported. However, the configuration and geometry of the combinations tested were different from the system proposed herein. Typically, the water jet was installed just ahead of the drag bit, as shown in Annex C.1, Figure C.1.1. For this configuration, the experimental results obtained are summarized in Annex C.1, Figures C.1.2 through C.1.12, and Annex C.2, Figures C.2.1 to C.2.3. For the proposal suggested in this appendix, shown in Figure C.3, it is necessary to test the relationship between the cutting or normal forces and the water-jet parameters. This will allow optimization of these basic parameters before full-scale tests proceed.

A critical function for the mining process is the depth, d_i, of the kerf and the distance, a, between adjacent kerfs. The resultant cutting force, F, is limited by the strength of the drag bit. Yet, on the other hand, this force, F, depends upon the sizes of the shear areas and on the mechanical properties of the rock. The shear area, A, is a function of geometrical and kinematical parameters, namely:

$$A = f\,[a \cdot (t_1 + d_c) \cdot \omega_2 t] \qquad (2)$$

where: ω_2 = angular velocity of the disc rotation

t = time

a = width of sheared area

t_1 = depth of sheared area

d = d_c as shown in Figure C.3.

When the shear area is not optimized, two results may occur:

(1) When the depth of the kerf is too large, the drag-bit tool may be broken.

(2) When the depth of the kerf is too small, the conventional mode of cutting will be performed without the water jet action improving the mining process.

The depth of the slots cut by the water jet can be calculated from the theory of hydraulic rock cutting, or may be interpolated from results of experimental test cutting. The parameters which control the water jet erodibility of the rock are not the same as those which control the resistance of the rock to ordinary mechanical destruction.

For rocks which are not too coarse-grained, the specific erodibility may be defined as follows:

$$E_{sp} = \frac{K_p}{\mu g} \qquad (3)$$

where: K_p = modified permeability calculated from average pore velocity

μ = viscosity of the water

g = grain size.

The depth, h, of the slot can then be calculated from equation (4):

$$h = E_{sp} \cdot p_0 \cdot \frac{d}{v} \qquad (4)$$

Note that equations (3) and (4) are only valid when:

$$\frac{d}{g} \gg 1 \qquad \text{and} \qquad \beta E_{sp} \frac{p_0}{D} \frac{d}{v} \ll 1$$

where: d = diameter of the water jet

v = traverse velocity of the jet

p = pressure of the jet

β = coefficient of pressure drop in the slot $\simeq 0.025$

D = width of slot = 2.5d.

The specific erodibilities for some rocks are presented in Annex C.3, Table C.3.2, and the depths of slots achieved experimentally are summarized in Annex C.4, Figure C.4.1 and Table C.4.2.

C.1.2 Heavy-Duty Impact Breaker with Water-Jet Augmentation

In this system, shown schematically in Figure C.4, the impact bit penetrates the rock in the same plane as the high-pressure water jet. Kinetic energy from the hydraulic piston is transferred through a steel rod into the impact bit by means of impact shock waves. Additional energy is released onto the rock surface by means of the high-pressure water jet. It is anticipated that this will be a very good mining method because:

- the high energy transfer allows breakage of very hard rocks
- the addition of a water jet to existing conventional machines will not influence the size of the machine working at the face of the tunnel
- there is greater manoeuvrability of the breaker as compared to full-face machines

- of the simplicity of the high-pressure water design without rotary jet action.

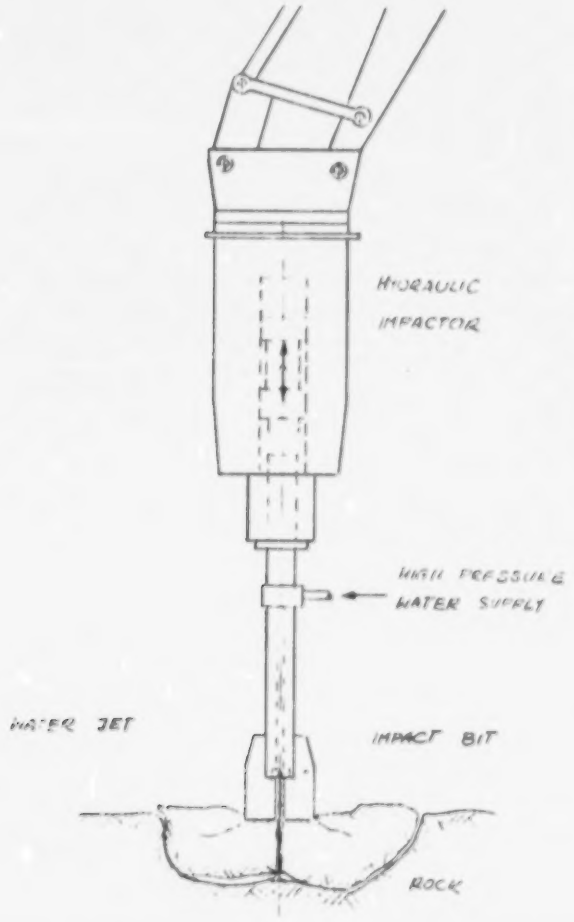

Figure C.4 Heavy-duty impact braker with water-jet augmentation

An understanding of the breakage phenomenon that can be expected with the combined action of the mechanical impact bit and high-pressure water jet may be found by examining each process separately.

C.1.2.1 Mechanical Wedge Penetration

The wedge penetration, as illustrated in Figure C.5, forms a crater. During chipping action, the rock is elastically deformed and surface

irregularities are crushed. The main crack encloses the wedge and radiates downwards through the subsurface. A zone of triaxial compression is formed around the wedge and secondary cracks propagate along shear trajectories to the surface. Penetration and chipping of the rock result from these applied stresses under the impact bit. The state of stress is compressive, and may be separated into two components: a uniform hydrostatic stress and a deviatoric stress, which is responsible for the failure phenomenon. The induced hydrostatic stress depends on the semi-included angle, 2β, of the impact bit. The larger the angle 2β, the larger force is required for a given depth of penetration, and a larger triaxial compression zone is formed. A simplified two-dimensional model for static penetration of brittle rock is proposed by Paul and Sikarskie to predict the gross behaviour of rock under bit penetration (see Figure C.5). This theory relates the impact force, P_i, to the corresponding cycle of chip formation, i, by the following equation:

$$P_1 = 2\sigma_c \frac{\sin\theta(1 - \sin\phi)}{1 - \sin(\theta + \phi)} \cdot d_i \qquad (5)$$

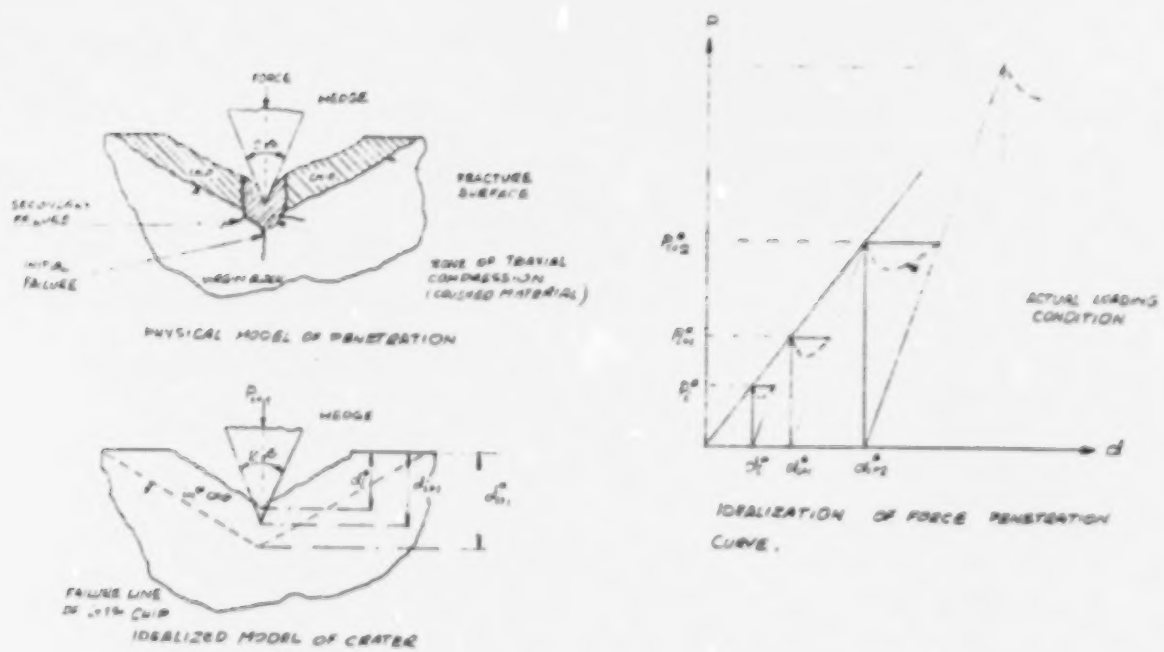

Figure C.5 Chip formation in rock

where: P_i = impact force for cycle i

σ_c = compressive strength of rock

θ = 2β = semi-included wedge angle

ϕ = angle of internal friction of rock.

The failure angle, ψ, of the chip is predicted by the relationship in equation (6), which allows calculation of the size of the chip removed:

$$\psi = 45° - \frac{\phi + \theta}{2} \qquad (6)$$

Note that experimental results show that the dynamic force required is more than double the static force as calculated in equation (5) to yield a given depth of penetration.

C.1.2.2 Water-Jet Penetration and Breakage of Rock

A water jet directed into one point of a rock penetrates it and initiates cracking. The water pressurizes these cracks which creates stresses, which in turn lead to breakage. No consistent theories presently exist which link mathematically the multiple action of water jets from an impact-type system to the rock properties. Drawing from "state-of-the-art" technology, predictions are only possible based on the experimental results of rock breakage by pulsed water jets. However, for practical applications, when the deficiency of mining by water jet is being investigated, the relationship between specific energy and pressure or pulse energy of the jet is required.

In Annex C.5, Figure C.5.1, the specific energy, SE (J/cm^3) is plotted against specific pressure, SP.

$$CP = P \div \sigma_c \qquad (7)$$

where: P = pressure

σ_c = compressive strength of rock.

The formula relating SE to SP is determined empirically from this curve and is expressed by the formula:

$$SE = 146{,}500.SP^{-1.035} \qquad (8)$$

which shows that specific energy tends to decrease for an increase in pulse energy (Annex C.5, Figure C.5.1). Similar relationships are observed for purely mechanical breakage (Annex C.6, Figures C.6.1 and C.6.3).

C.1.2.3 Combined Mechanical Wedge Plus Water Jet Action

Mechanical impact breaker bits may easily fracture rock, but the maximum blow energy of heavy-duty hydraulic impactors is limited to about 10 kJ. The combination of an impact breaker and a high-pressure water jet creates the possibility of multiplying this pulse energy. Pressurization of cracks by the water jet enhances stresses and accelerates the process of failure.

This proposed combination is similar to that of percussive drilling augmented by water jet. In Annex C.7, Figure C.7.1, percussive drilling speed is shown to be improved by approximately 40 per cent by the use of water jets.

C.1.3 "Boom"-Type Roadheader with Abrasive Water Jet Assistance

"Boom"-type roadheaders with different designs of cutting heads can be used for mining of rock within a limited range of rock hardness. Very high cutting and thrust forces are required to achieve reasonable and competitive advance rates in hard rock. The wear of cutting tools in such rock is so high that in many cases the cost of these tools becomes the limiting factor in the application of these machines in a hard rock environment. To overcome this deficiency, water jets may be used to cut kerfs and lubricate the tools (see subsection C.1.1). Pure water jet cutting ability in very hard and non-abrasive rock is very limited. In order to enhance the kerfing process of the water jet, abrasives may be added to the water. High-pressure water mixed with special

abrasives has the ability to cut deep slots in the hardest of materials, including steel.

The abrasive jet system suggested in this subsection may equally be applied to the Habegger-type machine of subsection C.1.1 with essentially the same scheme as shown in Figure C.1. The disadvantage of such a method for the circular tunnelling machine is the possibility of wear of cutting tools by abrasive particles. This will occur when the abrasive water jet is too close to the mechanical disc cutters.

However, for the roadheader machine combination, it is possible to eliminate this proximity problem. The proposed layout is shown in Figure C.6. In this case, one or more abrasive nozzles are installed on a boom or other traversing mechanism in order to cut slots of a certain pattern. An independently installed cutting head on the roadheader follows the nozzles after a time delay. This is to ensure that the cutting actions of the jets and mechanical cutters do not interfere with each other, and that the water will not abrade the mechanical cutters.

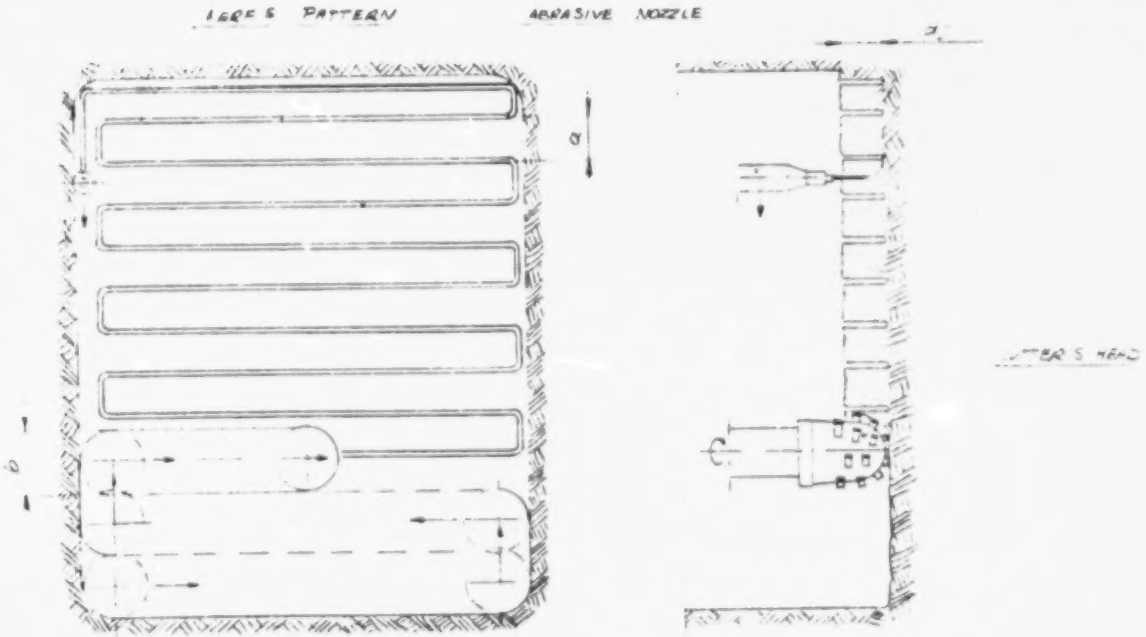

Figure C.6 Roadheader/water-jet configuration

This cutting action may be performed horizontally, as illustrated, or vertically.

Deep kerfs in the solid rock face create new free surfaces, and weaken the resistance of the rock to cutting and breaking performed by the mechanical cutter. In general, a similarity between this cutting method and that described in subsection C.1.1 can be assumed. The ratio, b/a, and the kerf depth, dj, as shown in Figure C.6, should be determined experimentally for the best performance of this system.

Many parameters influence the depth of kerf cut by abrasive water jets. The simplified equation relating these parameters as derived by Hashish[3] is shown below in equation (9). It illustrates the most important factors which affect abrasive jet cutting.

$$h = \frac{C}{2\,(1+R)} \cdot \sqrt{\frac{\dot{m}\,P}{\rho\sigma u}} + \frac{4\,(1-c)\,\dot{m}\,P}{\pi\rho\,\mathcal{E}\,u\,d\,(1+R)^2} \qquad (9)$$

where: h = depth of cut

c = ratio dependant on jet diameter

R = abrasive-to-water mass flow ratio = $\dot{m}/m_w$

$\dot{m}$ = abrasive mass flow rate

P = water upstream pressure

ρ = water density

σ = flow strength

u = traverse rate

$\mathcal{E}$ = energy required to remove unit volume by deformation wear

d = jet diameter.

Some results of experimental abrasive water jet cutting in rock are presented in Annex C.8.

C.2 MECHANICAL CONFIGURATION OF THE PROPOSED SYSTEMS

The three proposed machine configurations for tunnelling in rock each use existing mining machines with the addition of some form of water jet. Two types of water jet are available: pure high-pressure-water or abrasive-water jet. Similarly, two pressure-generation systems are available commercially and are both manufactured by Indescor. These are plunger (positive displacement) high-pressure pumps, and intensifier pumps.

C.2.1 High-Pressure Water Systems for Jet Formation - An Overview

C.2.1.1 Plunger Pump Systems

These high-pressure pumps are manufactured mostly (with three pistons) as triplex plunger pumps. They may be assembled in conjunction with either diesel or electric motors. The high-powered plunger pumps are used in systems where a high discharge volume of water is required. The pressure in the plunger pumps is limited by the replacement life of the plunger packing and by the fatigue strength of the body. Generally such pumps are restricted to pressures of 20,000 psi (140 bars). Limitations are also placed on the system by the strength of hoses, fittings, pipes, etc. At this time the maximum working pressure for high volumes for a flexible hose available on the market is 22,000 psi. Although it is possible to transfer flows in volumes like 15 gpm (65 lpm) at 20,000 psi pressure through heavy-duty steel pipes and swivel joints, a very bulky and complicated system is required.

Essentially, systems which use plunger pumps may be used practicably when pressures do not exceed 20,000 psi. The delivery volume is limited, by the size of the motor used and by the design parameters of the system, to about 20 gpm (72 lpm) at 20,000 psi. For lower working pressures, a higher volume may be discharged. Power, pressure and volume are all related by the equation:

$$BHP = \frac{Q \times P}{1714\eta}$$

where: BHP = brake horsepower

P = pressure (psi)

Q = volume (gpm)

η = mechanical efficiency, usually 80 to 90 per cent.

C.2.1.2 Intensifier Pump Systems

A simplified schematic of an intensifier system is shown in Annex C.9. The unit consists of a low-pressure oil pump circuit and an intensifier. The intensifier transfers low-pressure, high-volume oil flow into very-high-pressure, low-volume water flow. This system has great universality due to the oil-hydraulic first stage, which can be adapted to special designs. For the configurations discussed in this appendix, it may be possible to utilize existing suitable systems. Maximum working pressures from commercially available intensifiers are in the order of 60,000 psi (420 bars). At such pressures, the discharge volume from one double-acting intensifier is up to 2 gpm. This volume is also the limit for high-pressure tubings and swivels at 60,000 psi. More than one intensifier may be used in a system, supplied from one or more hydraulic pumps, which can expand the capacity up to 6 gpm at 60,000 psi. This will require about 300 hp of installed motors. Some disadvantages of intensifier systems are:

- limitation of a low discharge volume from one intensifier
- lower mechanical efficiency than for plunger pumps, η = 60 to 70 per cent
- high rate of pulsation of pressure which generates the need for a hydraulic accumulator within the system

- the cost per unit horespower installed of an intensifier pump is five times greater than that for a plunger pump.

C.2.2 Machine Assembly for Circular-Type Tunneller

For detailed design of the proposed configuration of the Habegger-type circular machine for tunnelling hard rock combined with water-jet assistance, it is necessary to undertake suitable experimental tests and consultations with the manufacturer. The simplified schematic shown in Figure C.7 is thus merely intended to clarify the combination concept.

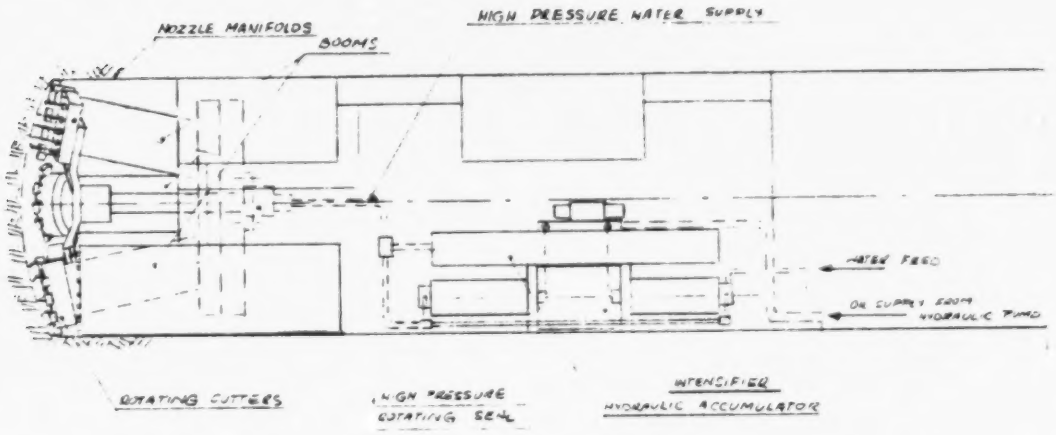

Figure C.7 Habegger-type circular machine with water-jet assistance

Nozzles are installed in two or four manifolds, and high-pressure water is supplied from the pump through high-pressure tubing through a rotating seal. The intensifier is supplied with low-pressure hydraulic oil from the hydraulic pump. The number and size of the nozzles should be chosen according to the kerfing needs, and determination of these will be at the first stage of the development. Small-diameter 0.005 to 0.015 inch (0.127 to 0.381 mm) sapphire orifices are usually used in these low-volume, high-pressure intensifier systems.

It is suggested that the pumping system be of the intensifier type for plain water-jet cutting, since this action requires greater than the 20,000 psi threshold pressure to cut certain rocks. Intensifiers are also relatively small and compact so that one or more intensifiers may be installed inside the tunnelling machine. The manifolds with nozzles, connected by high-pressure tubing to the rotating seal, are rotated at the same speed as the boom.

Accurate prediction of the performance of the described hybrid machine is difficult without experimental test data. Assuming that this combination will improve the advance rate similar to other tested hybrid methods using water-jet enhancement, the performance may be improved 50 to 100 per cent over purely mechanical cutting. Also, the application of this tunnelling machine could be extended to harder rocks, where only the drill-and-blast method has been used to date. An improvement of 50 per cent in the advance rate as a result of an increase in investment cost, which could be as little as 10 per cent, is very favourable.

C.2.3 Impactor "Boom"-Type Breaker with High-Pressure Water Assembly

This combination is the simplest to construct from the engineering point of view. Existing impactors are installed, usually on a crawler base unit with a loader attached. The impact tool should be redesigned for water-jet purposes to allow the execution of two functions:

- transfer of impact shock waves to the rock
- high-pressure water jet transmission to the rock.

The connection of the high-pressure water supply to the impact tool is not necessarily rotary. The required pressure and volume inputs of the water should be tested in relation to the impact energy and the rock properties. This primary test will indicate whether a plunger pump or intensifier system should be used to supply high-pressure water, and thus whether flexible hoses or steel tubing with swivels are required.

The system shown schematically in Figure C.8 consists of a hydraulic impactor installed on a crawler base unit, with the water supplied by an intensifier pump unit. This unit may be mounted on a wheeled base and towed by the mobile crawler unit. The high-pressure water is supplied directly to the impact tool. Due to the boom-type construction of the breaker, it can mine rock for virtually any shape of tunnel.

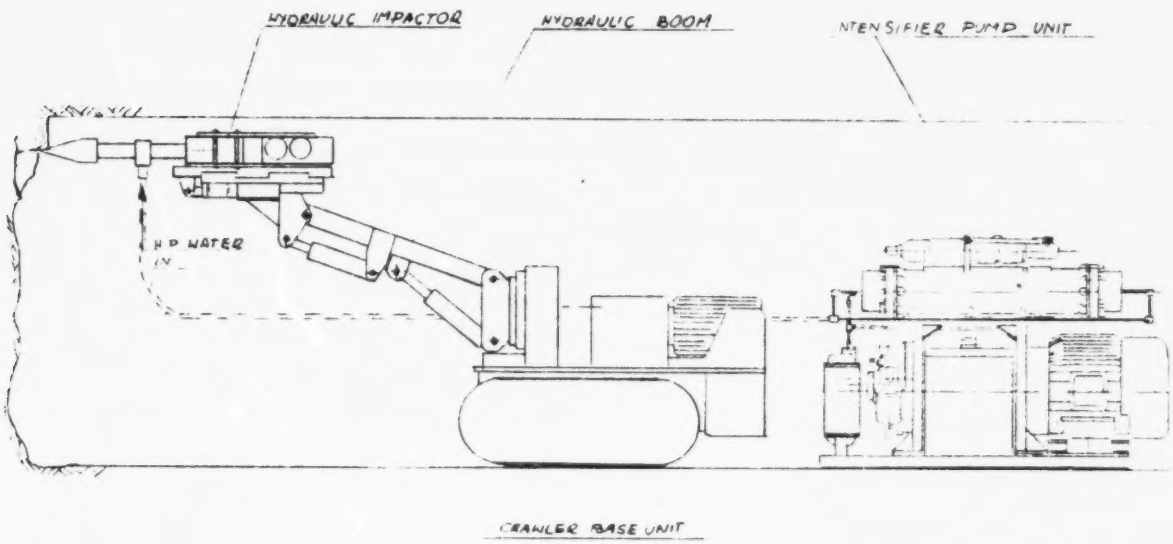

Figure C.8 "Boom"-type impactor with High-Pressure Water Assembly

A combination of impact breaker with water jets has not been tested on a commercial scale. Laboratory tests have been performed by the author, although insufficient data have been collected to allow calculation of the efficiency of the mining method described. Therefore, is is suggested that experiments be undertaken, including the investigation of the hydrodynamical parameters of the jet, and the geometrical configuration of the impact bit.

Although many tests should be performed to optimize the system, the simplicity of this combination creates the opportunity to achieve good results in a reasonably short period of time. The versatility of this design is characterized by the variety of tunnel sizes that it is possible to mine with such a machine, and the flexibility in the number of impactors that may be used in one system.

C.2.4 Combination of "Boom"-Type Roadheader with Abrasive Water-Jet System

This configuration may be arranged in two ways. The first arrangement consists of a kerfing nozzle system operating on a machine separate from the mechanical cutting head, or where the nozzles work from the same boom as the cutters, but in the following sequence. The second arrangement consists of the kerfing nozzle system and the cutting head installed on the same machine, but on two separate booms.

The former system is much more suitable for this stage of the development process, because existing "boom"-type mining machines may be readily adapted to the technology required for these operations. The latter system is a second-stage development which can be made when all the system requirements have been determined and tested. In the first stage, it will be easier to use two existing machines, which will be more economical and also more flexible for research purposes.

To break and cut rock which has already been slotted by abrasive water jet, any "boom"-type mining roadheader may be used. A multiple abrasive jet nozzle manifold can be attached to a jumbo-type drill boom on a special-purpose-designed mobile machine, or it can be attached to the boom of the roadheader of Figure C.9. This system, as shown in Figure C.9, operates in two sequences:

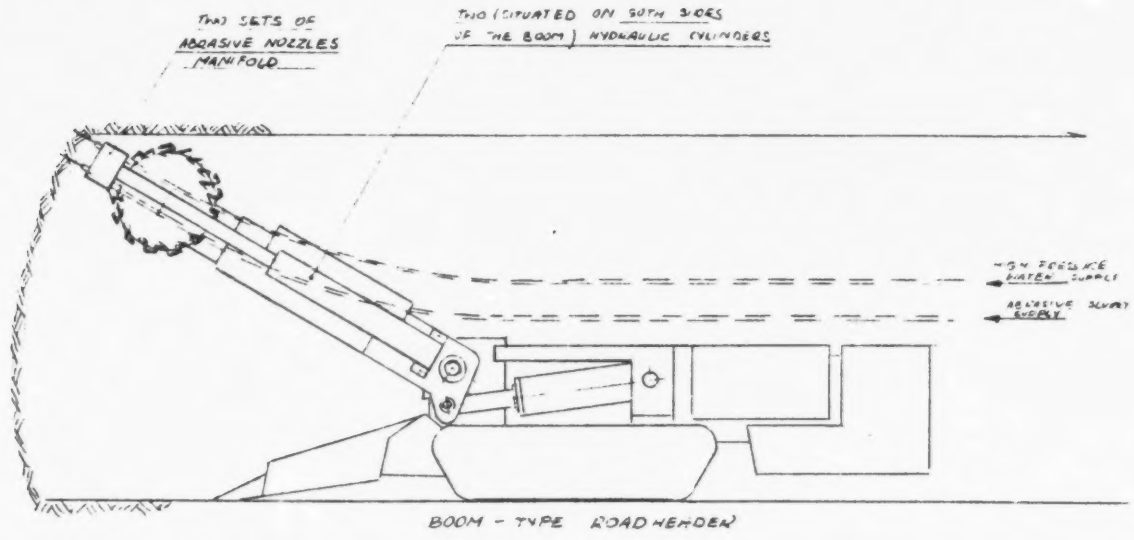

Figure C.9 "Boom"-type roadheader with abrasive water-jet system

(1) Kerfing is performed by the abrasive water jets when the nozzle manifold is in an extended position, and the cutting head does not rotate.

(2) The nozzles are switched off, the manifold is retracted and cutting is performed by mechanical tools as the cutting head rotates.

The nozzles are supplied with high-pressure water from a plunger pump (10,000 to 20,000 psi) and the abrasive slurry is fed from a slurry pump unit. The very deep slot-cutting ability of the abrasive water jet should create the opportunity for the mechanical cutting head to perform efficiently in mining hard and very hard rock. There is not much literature on this hybrid method of mining, but this promising technique is currently being investigated in a few jet technology research centres.

C.4 PROPOSED DEVELOPMENT OF THE PREFERRED OPTION CONCEPT

The three proposed combination scenarios should be evaluated initially by performing some simple data acquisition tests to establish performance in different rock types.

The comparative test should be performed in very hard rocks and common rocks such as granite and limestone. All three options utilize high-pressure water jets, though for the third scenario with a roadheader machine, either an intensifier or plunger pump can be used as the source of the water jet. An intensifier system can generate sufficiently high pressure for non-abrasive water to cut hard rock.

Generally, the experimental set of equipment requires:

- intensifier pump unit, approximately 100 hp, generating up to 50,000 psi pressure
- abrasive slurry supply unit, capacity 2 gpm
- "boom"-type roadheader with the capability to install either a hydraulic impactor or rotating cutting head

- heavy-duty hydraulic impactor
- high-pressure tubings, fittings and swivels
- manifolds and nozzles for pure water and abrasive water jets.

This equipment is essential for the first-stage comparative test. A plunger pump is not included in this list, since all cutting functions may at this time be performed utilizing an intensifier pump, with or without abrasives in the jet. At later stages, a plunger pump may be required to provide sufficient volume to meet the parameters that will be derived initially.

The initial comparative tests should be performed in equal rock conditions for all three combinations, employing similar power of the water jets and tools. Measurements will include the volume of rock removed and the time for the mining. The cutting and thrust forces of the mechanical tools should be recorded. Results of these tests will be evaluated in order to indicate the optimum solution in terms of engineering and economics.

On the basis of the results from this primary set of tests, the following parameters of the testing machines should be calculated:

- required pressure range of water jets
- required volume of water and total installed pump power
- range of kinematical parameters for nozzle movement
- thrust and cutting forces acting on one and the whole set of cutting or breaking tools
- maximum thrust of the machine on the rock during the mining action
- required torque on the rotating mechanical cutting head
- rough estimation of mined rock output versus loader and conveyor capacity.

The first-stage design of a water-jet-assisted machine for tunnelling in hard rock should be flexible. It is important that there should be an ability to adjust, within a certain range, the geometrical parameters regarding the nozzles, such as distance between the nozzles and the position of the nozzles in relation to the cutting tools. Kinematical parameters of the jets such as water pressure and speed of nozzle rotation should also be variable. Nozzle design should allow the change of the orifice size within the nozzle when sapphire orifices are used. This system flexibility permits the optimization of machine performance.

The next stage development will consist of the design and testing of a prototype tunnelling machine with high-pressure water or abrasive-water-jet assistance.

C.5 CONCLUSIONS

The three proposed hybrid configurations for tunnelling are recognized as promising new methods for improving the speed of mining in hard rocks. The first combination of water jets with a circular-type tunnelling machine is well suited to large-diameter tunnels, where high-speed, continuous boring may be required.

The second method, which utilizes water jets and an impact breaker, is appropriate for small-size tunnels, and hard but brittle rocks. Although the impactor is capable of breaking large sections from solid rock, the total operating efficiency will be influenced by the time lost in shifting the impactor from one breaking area to the next.

The third system, which uses a "boom"-type roadheader combined with abrasive water jets which can cut the hardest materials, may be used for tunnelling in very hard rocks. An important factor in this design is the cost of the abrasives used in the water-jet process and whether the improvement in mining efficiency justifies their cost.

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ANNEX C.1

RESULTS OF TESTS OF WATER-JET ASSISTANCE TO DRAG BIT

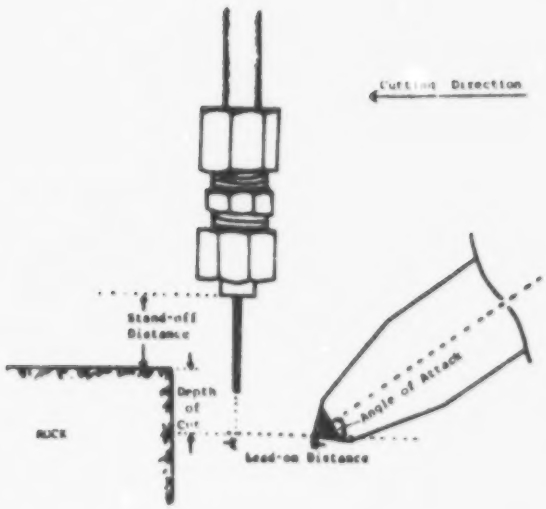
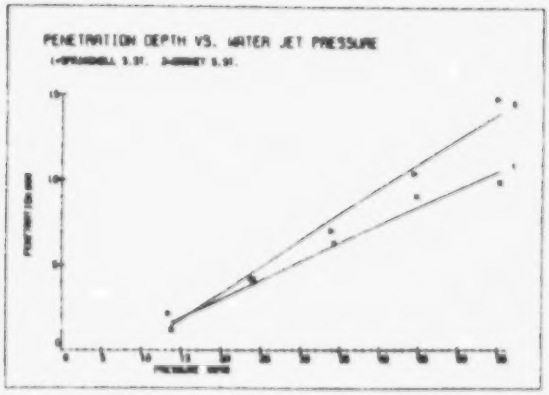


Figure C.1.1



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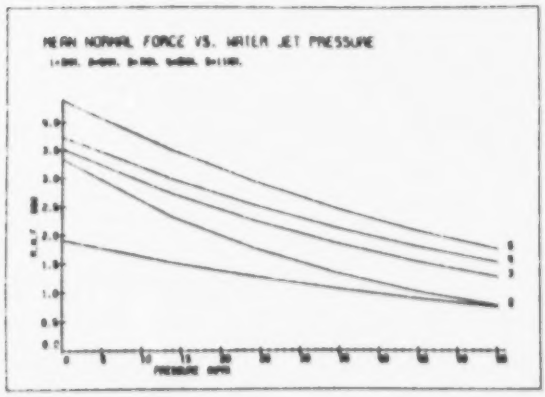

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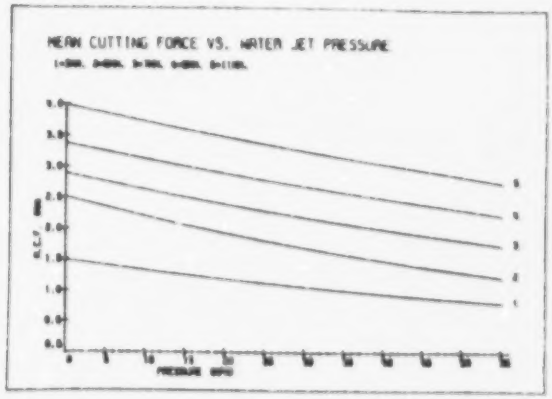

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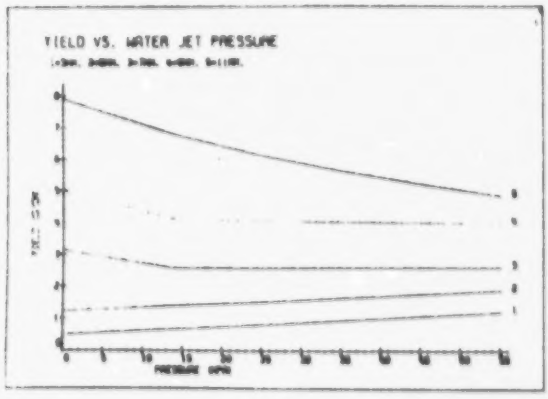


Figure C.1.5

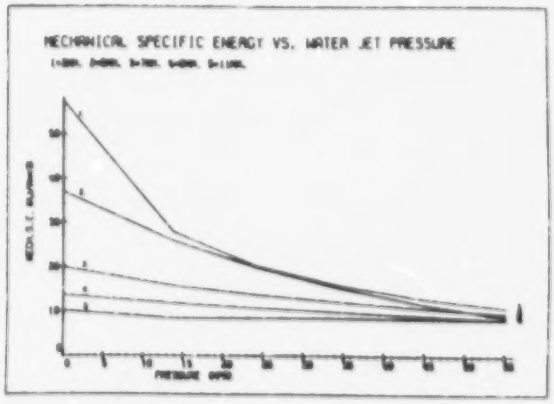


Figure C.1.6

Figures C.1.1 - C.1.6 Effect of water-jet assist on cutting parameters

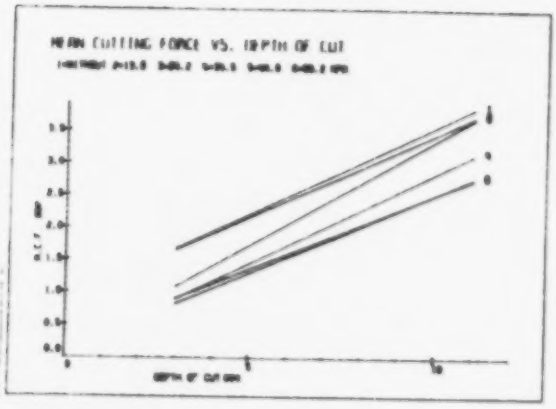
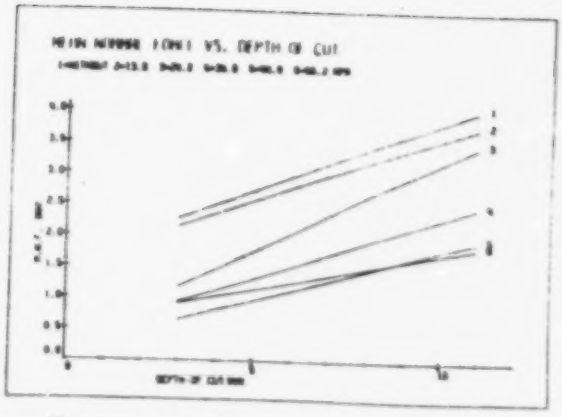


Figure C.1.7



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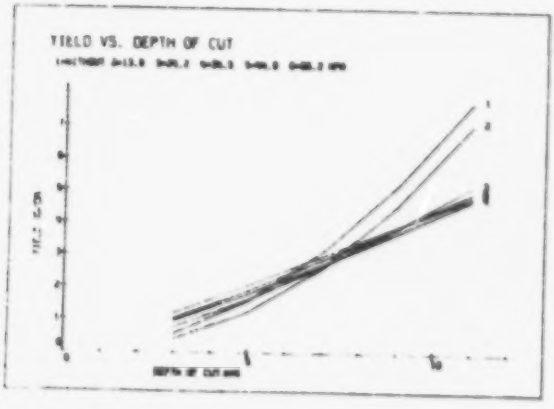
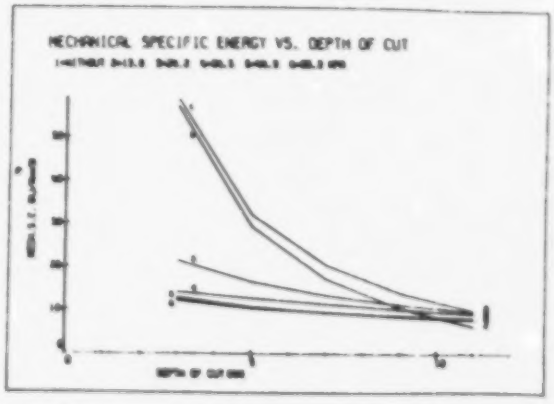


Figure C.1.9



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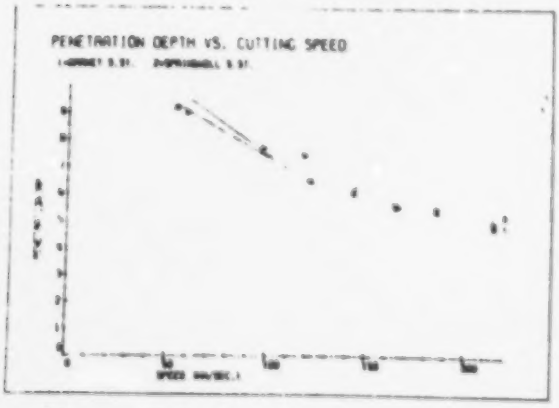


Figure C.1.11

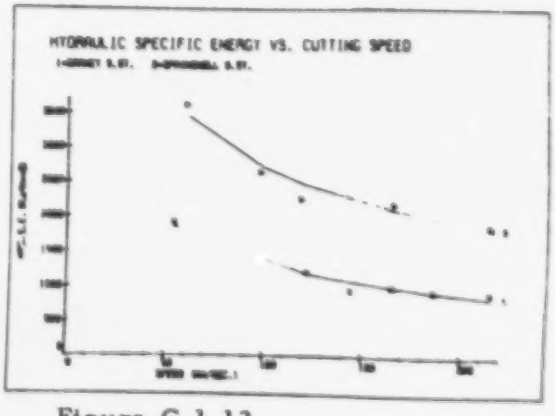


Figure C.1.12

Figures C.1.7 - C.1.12 Effect of water-jet assist on cutting parameters

ANNEX C.2

CUTTING SANDSTONE BY DRAG BIT -- WATER-JET SYSTEM

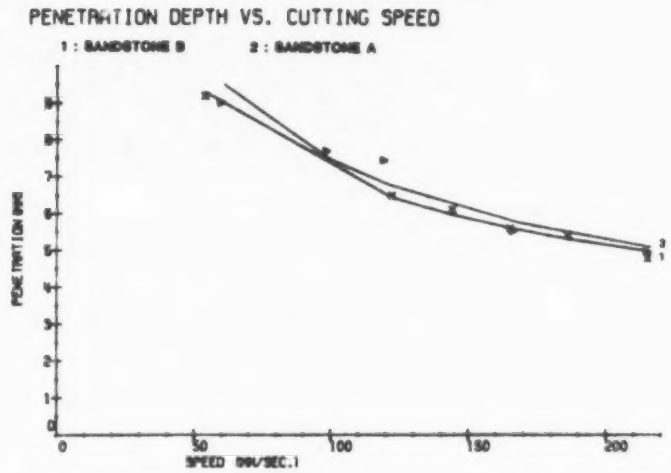


Figure C.2.1 Traverse speed/penetration relationship

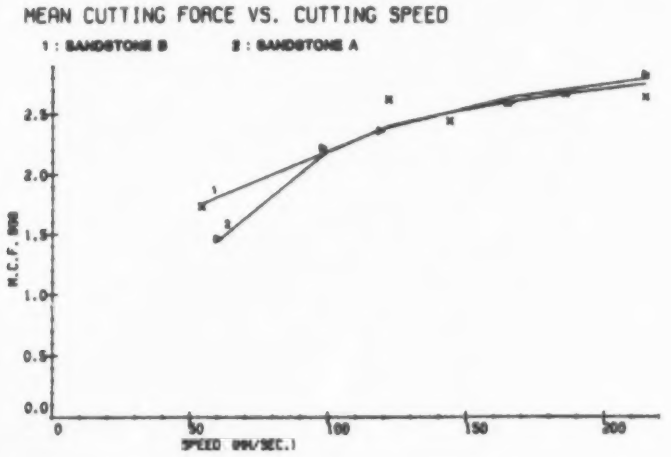


Figure C.2.2 Traverse speed/mean cutting force relationship

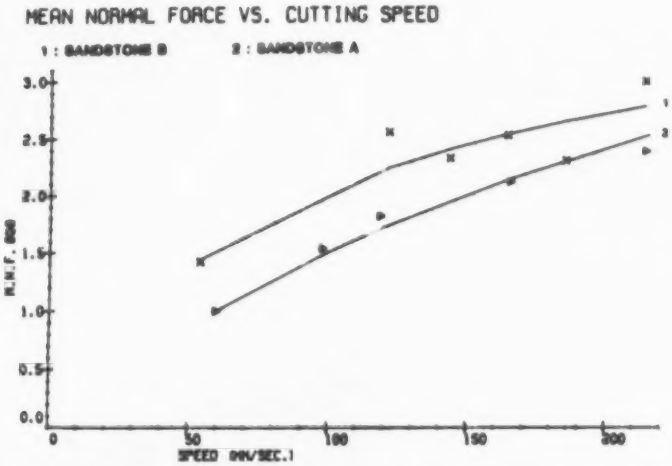


Figure C.2.3 Traverse speed/mean normal force relationship

ANNEX C.3

SPECIFIC ERODIBILITY OF ROCKS

TABLE C.3.1

ROCKS THAT HAVE BEEN INVESTIGATED WITH RESPECT TO THEIR SPECIFIC ERODIBILITY (THE COLUMN TO THE RIGHT SHOWS WHERE THE EXPERIMENTAL DATA COME FROM)

Berea sandstone	Harris & Mellor (Ref. 1), Crow (Ref. 2)
Wilkeson sandstone	Crow (Ref. 3)
Darley Dale sandstone	Page (Ref. 4), Arlingstall & Moodie (Ref. 5), Rehbinder (Ref. 7)
Pennant sandstone	Arlingstall & Moodie (Ref. 5)
St Bees sandstone	Page (Ref. 4)
Horseforth sandstone	Page (Ref. 4)
Lemunda sandstone	Rehbinder (Ref. 7)
Albringhausen sandstone	Rehbinder (Ref. 7)
Red sandstone	Arlingstall & Moodie (Ref. 5)
Bohus granite	Rehbinder (Ref. 7)
Stockholm granite	Rehbinder (Ref. 7)
Red granite	Fun Den Wang (Ref. 6)
Titania Diabase	Rehbinder (Ref. 7)
Kiruna Quartz Porphyry	Rehbinder (Ref. 7)

TABLE C.3.2

THE SPECIFIC ERODIBILITY OF ROCKS PRESENTED IN TABLE C.3.1

ROCK		Specific erodability determined by equ (5) m^3/Ns	Specific erodability determined by equ (6) m^3/Ns	Average specific erodability m^3/Ns
Berea sandstone				$8 \cdot 10^{-8}$
	(Ref. 1)	$4 \cdot 10^{-8}$	$11 \cdot 10^{-8}$	
	(Ref. 2)	$7 \cdot 10^{-8}$	$8 \cdot 10^{-8}$	
Wilkeson sandstone	(Ref. 3)	$4 \cdot 10^{-8}$		$4 \cdot 10^{-8}$
Darley Dale sandstone				$11 \cdot 10^{-8}$
	(Ref. 4)	$11 \cdot 10^{-8}$		
	(Ref. 5)		$9 \cdot 10^{-8}$	
	(Ref. 7)	$12 \cdot 10^{-8}$		
Pennant sandstone				$6 \cdot 10^{-8}$
	(Ref. 5)		$5 \cdot 10^{-8}$	
	(Ref. 7)	$6 \cdot 10^{-8}$		
St Bees sandstone	(Ref. 4)	$4 \cdot 10^{-8}$		$4 \cdot 10^{-8}$
Horseforth sandstone	(Ref. 4)	$10 \cdot 10^{-8}$		$10 \cdot 10^{-8}$
Lemunda sandstone	(Ref. 7)	$8 \cdot 10^{-8}$		$8 \cdot 10^{-8}$
Albringhausen sandstone	(Ref. 7)	$4 \cdot 10^{-8}$		$4 \cdot 10^{-8}$
Red sandstone	(Ref. 5)		$10 \cdot 10^{-8}$	$10 \cdot 10^{-8}$,
Bohus granite	(Ref. 7)	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
Stockholm granite	(Ref. 7)	$1 \cdot 10^{-8}$		$1 \cdot 10^{-8}$
Red granite	(Ref. 6)	$3 \cdot 10^{-8}$	$3 \cdot 10^{-8}$	$3 \cdot 10^{-8}$
Titania Diabase	(Ref. 7)	$1 \cdot 10^{-8}$		$1 \cdot 10^{-8}$
Kiruna Quartz Porphyry	(Ref. 7)	$2 \cdot 10^{-8}$		$2 \cdot 10^{-8}$

ANNEX C.4

RESULTS OF TESTS WITH HIGH-PRESSURE WATER-JET CUTTING

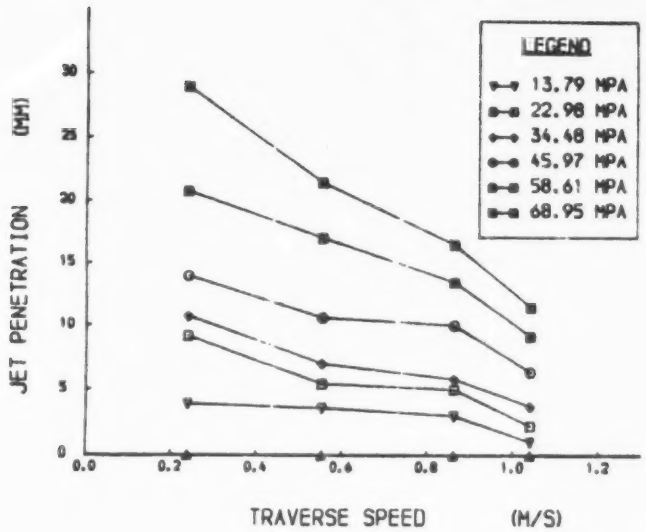


Figure C.4.1 Traverse speed penetration relationship for Sandstone C

TABLE C.4.1

ROCK PROPERTIES

Rock Properties	Rock Types		
	Milford Pink Granite	Indiana Limestone	Massillon Sandstone
Young's Modulus bars x 10^5	3.48	1.60	0.97
Poisson's Ratio	0.22	0.20	0.24
Compressive Strength bars x 10^2	22.0	3.31	3.10
Tensile Strength bars	76.5	42.0	12.7
Dilatational Velocity m/sec x 10^3	4.60	3.86	2.86
Distortional Velocity m/sec x 10^3	2.68	2.07	1.12
Schmidt Hammer	50	30	39
Shore Scleroscope	88	15	15
Bulk Density kg/m^3	2628	2211	2019

TABLE C.4.2

DATA AND RESULTS OF TEST PROGRAM

Test No.	Pressure bars	Specific Pressure	Material	Traversing Rate cm/sec	Depth cm	Crater Dia or Slot Width	Volume cc	Energy J	Specific Energy J/cc
1	4,485	13.73	Limestone	0	8.38	.45	2.3	20,032	8,709
2	3,859	11.81	Limestone	0	4.31	.43	1.48	16,102	10,879
3	3,808	11.66	Limestone	0	2.54	.43	1.45	15,801	10,897
4	1,505	4.61	Limestone	0	.95	.38	.16	4,055	25,343
5	5,731	17.55	Limestone	0	8.12	.48	3.9	28,606	7,334
6	5,234	17.10	Sandstone	0	3.49	.48	3.1	25,087	8,092
7	1,113	3.63	Sandstone	0	.33	.38	.08	2,595	32,437
8	2,473	8.08	Sandstone	0	1.98	.38	.58	8,425	14,527
9	2,327	7.60	Sandstone	0	1.58	.38	.44	7,692	17,484
10	4,853	15.85	Sandstone	0	3.96	.45	2.6	22,472	8,643
11	4,725	15.43	Sandstone	0	3.50	.45	2.4	21,600	9,000
12	6,028	19.69	Sandstone	0	5.25	.48	4.3	30,784	7,159
13	7,551	3.47	Granite	0	.96	.157	1.0	42,599	42,599
14	7,161	3.3	Granite	0	.96	.198	.9	39,478	43,865
15	5,842	2.69	Granite	0	.63	.198	.6	29,385	48,975
16	3,561	1.64	Granite	0	.25	.198	.17	14,328	84,283
17	4,898	2.25	Granite	0	.33	.198	.37	22,758	61,510
18	3,897	1.79	Granite	0	.22	.198	.22	16,341	74,281
19	3,681	1.69	Granite	0	.15	.198	.19	15,039	79,157
20	1,086	.498	Granite	0	.06	.198	.01	2,480	248,042
21	4,968	2.28	Granite	0	.347	.198	.39	23,221	59,542
22	894	.412	Granite	0	.07	.198	.01	1,873	187,300
23	4,263	13.05	Limestone	10.16	2.54	.236	5.0	19,641	3,928
24	4,026	12.33	Limestone	10.16	3.49	.317	8.0	18,023	2,252
25	2,752	8.42	Limestone	10.16	2.37	.317	8.0	10,186	1,273
26	5,619	17.2	Limestone	10.16	3.33	.317	7.0	29,712	4,244
27	7,578	23.2	Limestone	10.16	3.81	.276	9.0	46,537	5,170
28	7,749	23.7	Limestone	10.16	3.01	.276	7.0	48,125	6,875
29	6,982	21.3	Limestone	40.64	3.33	.198	11.0	41,163	3,742
30	6,422	19.6	Limestone	40.64	4.44	.198	12.0	36,307	3,025
31	6,261	19.17	Limestone	40.64	3.81	.198	11.0	34,949	3,177
32	3,763	11.52	Limestone	40.64	3.49	.198	10.0	16,289	1,628
33	4,989	15.28	Limestone	40.64	3.17	.198	9.0	24,684	2,762
34	6,102	18.68	Limestone	40.64	2.54	.198	8.0	33,630	4,203
35	3,114	9.53	Limestone	40.64	2.69	.198	8.0	12,259	1,532
36	2,431	7.44	Limestone	40.64	2.69	.198	8.0	8,458	1,057
37	2,400	7.35	Limestone	0	2.0	.38	.50	8,053	16,106
38	2,363	1.08	Granite	0	.07	.22	.06	7,872	131,215
39	4,017	13.12	Sandstone	0	3.17	.43	1.7	17,071	10,041
40	5,376	17.56	Sandstone	0	3.81	.48	2.45	26,042	10,629

TABLE C.4.2 (Cont'd)

DATA AND RESULTS OF TEST PROGRAM

Test No.	Pressure bars	Specific Pressure	Material	Traversing Rate cm/sec	Depth cm	Crater Dia or Slot Width cm	Volume cc	Energy J	Specific Energy J/cc
41	7,653	25.0	Sandstone	0	7.93	.53	7.7	43,473	5,645
42	8,341	25.54	Limestone	0	11.76	.50	10.0	49,161	4,916
43	5,199	15.92	Limestone	0	8.25	.45	3.0	24,824	8,274
44	9,931	30.4	Limestone	0	16.94	.50	14.4	63,134	4,384
45	9,459	30.9	Sandstone	0	21.41	.53	12.7	58,867	4,635
46	9,289	28.44	Limestone	0	13.97	.50	12.0	57,374	4,781
47	9,272	4.27	Granite	0	.86	.198	1.7	57,222	33,660
48	8,540	26.15	Limestone	40.64	4.76	.317	14.0	55,679	3,977
49	9,598	29.3	Limestone	10.16	4.28	.317	11.0	66,338	6,030
50	9,148	28.0	Limestone	10.16	3.96	.317	12.0	61,724	5,143
51	10,832	33.17	Limestone	10.16	3.64	.317	10.0	79,533	7,953
52	7,700	23.58	Limestone	10.16	4.44	.396	13.0	47,669	3,666
53	2,931	8,96	Limestone	10.16	3.49	.317	8.0	11,197	1,399
54	5,989	18.3	Limestone	10.16	3.3	.317	8.0	32,695	4,086
55	6,164	18.9	Limestone	10.16	2.54	.317	7.0	34,146	4,878
56	10,340	31.7	Limestone	10.16	4.76	.396	14.0	74,171	5,297
57	8,721	26.7	Limestone	10.16	4.60	.317	13.0	57,451	4,419
58	9,401	28.8	Limestone	0	16.05	.53	12.7	58,356	4,594
59	7,985	24.4	Limestone	0	10.08	.53	8.5	46,222	5,437
60	8,384	25.6	Limestone	0	11.43	.50	9.5	49,521	5,212
61	11,292	34.5	Limestone	0	19.48	.53	19.5	75,994	3,897
62	10,499	32.1	Limestone	10.16	11.43	.317	23.0	75,891	3,299
63	10,823	33.9	Sandstone	0	20.32	.53	16.0	67,252	4,203
64	9,660	31.5	Sandstone	0	19.68	.53	13.5	60,663	4,493
65	8,902	29.0	Sandstone	0	15.39	.53	11.2	53,980	4,819
66	6,759	22.0	Sandstone	0	10.49	.50	5.7	36,327	6,373
67	11,335	36.3	Sandstone	0	20.82	.53	18.5	75,700	4,091
68	9,614	29.4	Limestone	10.16	4.12	.39	12.0	66,507	5,542
69	11,951	36.6	Limestone	0	21.59	.53	22.2	82,275	3,706
70	11,077	36.1	Sandstone	0	20.32	.53	18.5	73,807	3,989
71	10,005	32.6	Sandstone	0	20.57	.53	14.7	63,806	4,340
72	11,759	5.41	Granite	0	2.40	.23	3.1	80,380	25,929
73	7,444	24.3	Sandstone	0	11.88	.50	7.7	41,766	5,424
74	10,161	31.1	Limestone	40.64	4.28	.23	14.0	72,254	5,161
75	680	2.08	Limestone	10.16	1.11	.31	.90	1,251	1,388
76	1,360	4.16	Limestone	10.16	1.676	.31	1.35	3,540	2,622
77	2,040	6.25	Limestone	10.16	2.15	.31	1.74	6,503	3,737
78	2,721	8.33	Limestone	10.16	2.69	.31	2.17	10,012	4,614
79	3,401	10.41	Limestone	10.16	3.32	.31	2.68	13,993	5,221
80	4,081	12.50	Limestone	10.16	3.58	.31	2.88	18,394	6,387
81	4,387	13.43	Limestone	10.16	3.60	.31	2.90	20,502	7,069
82	5,170	15.83	Limestone	10.16	3.81	.31	3.07	26,223	8,541
83	5,850	17.91	Limestone	10.16	4.59	.31	3.70	31,565	8,531
84	6,464	19.77	Limestone	10.16	5.08	.31	4.09	36,648	9,162
85	7,074	21.66	Limestone	10.16	5.53	.31	4.46	41,977	9,411
86	2,040	6.25	Limestone	40.64	2.66	.198	5.36	6,503	1,213
87	2,721	8.33	Limestone	40.64	2.71	.198	5.46	10,012	1,833
88	3,401	10.41	Limestone	40.64	2.74	.198	5.51	13,993	2,539
89	4,081	12.5	Limestone	40.64	2.75	.198	5.54	18.394	3,320
90	4,761	14.58	Limestone	40.64	2.75	.198	5.54	23,179	4,183
91	5,442	16.66	Limestone	40.64	2.75	.198	5.51	28,320	5,139

ANNEX C.5

SPECIFIC ENERGY IN BREAKING ROCKS BY WATER JET

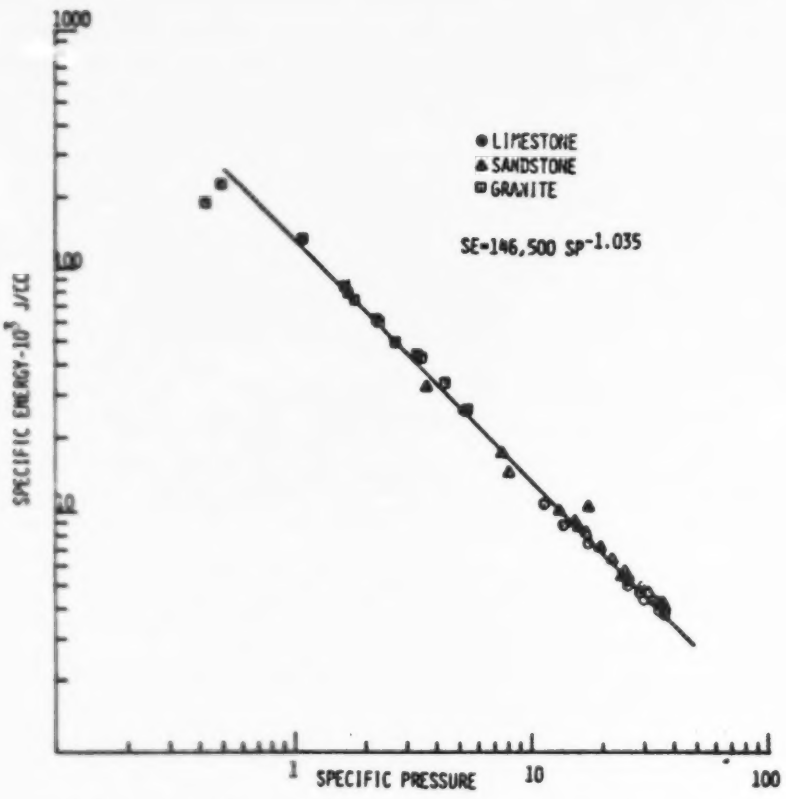


Figure C.5.1 Plot of specific energy versus specific pressure for stationary shots

ANNEX C.6

MECHANICAL AND HYDRAULIC ROCK BREAKAGE COMPARISON

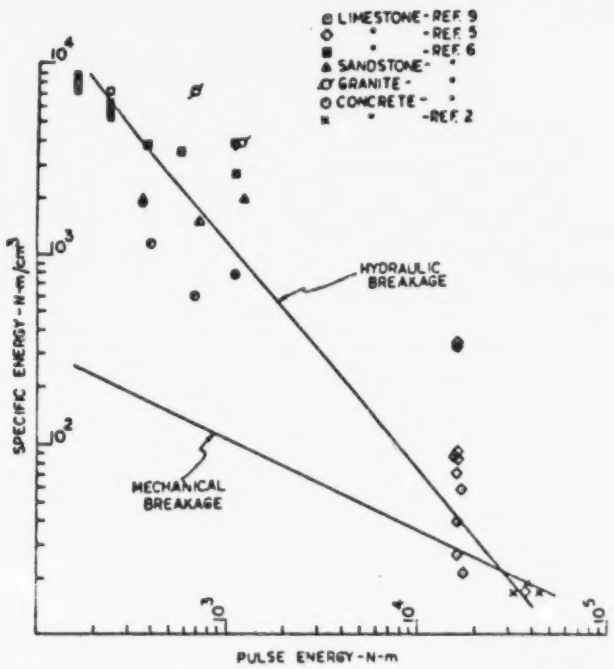


Figure C.6.3 Specific energy versus pulse energy

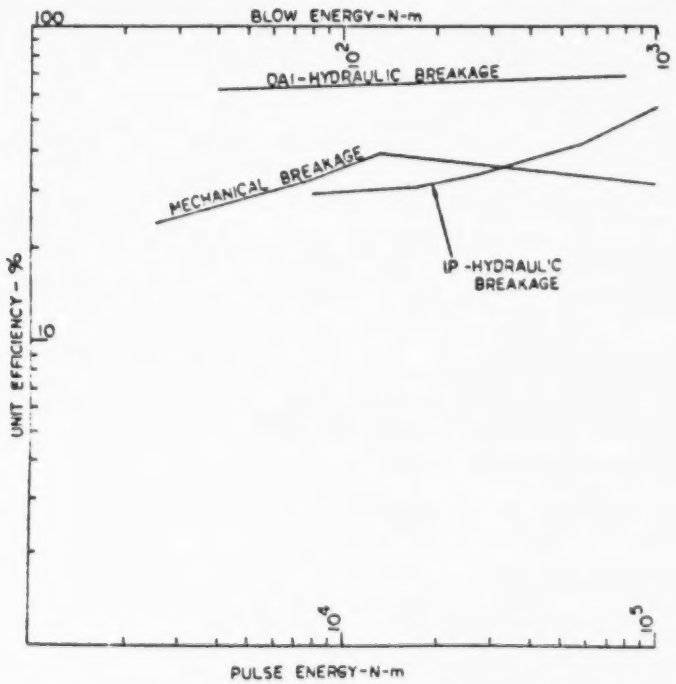


Figure C.6.4 Efficiency versus pulse/blow energy

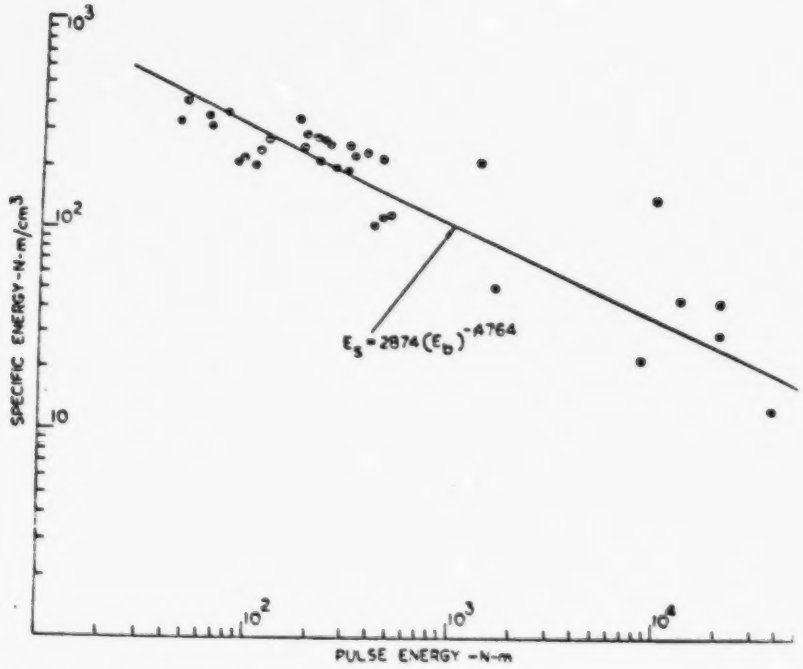


Figure C.6.1 Specific energy versus pulse energy for mechanical breakage

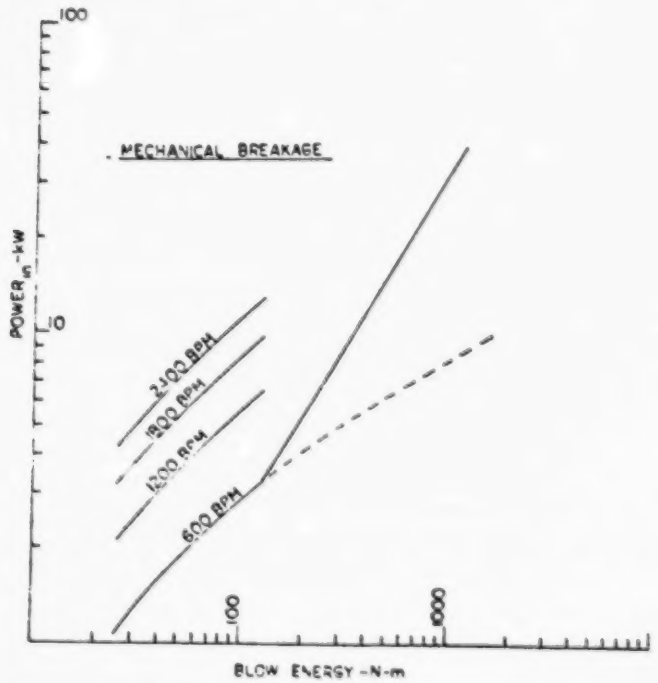


Figure C.6.2 System size versus blow energy

ANNEX C.7

PERCUSSIVE DRILLING WITH WATER-JET ASSISTANCE

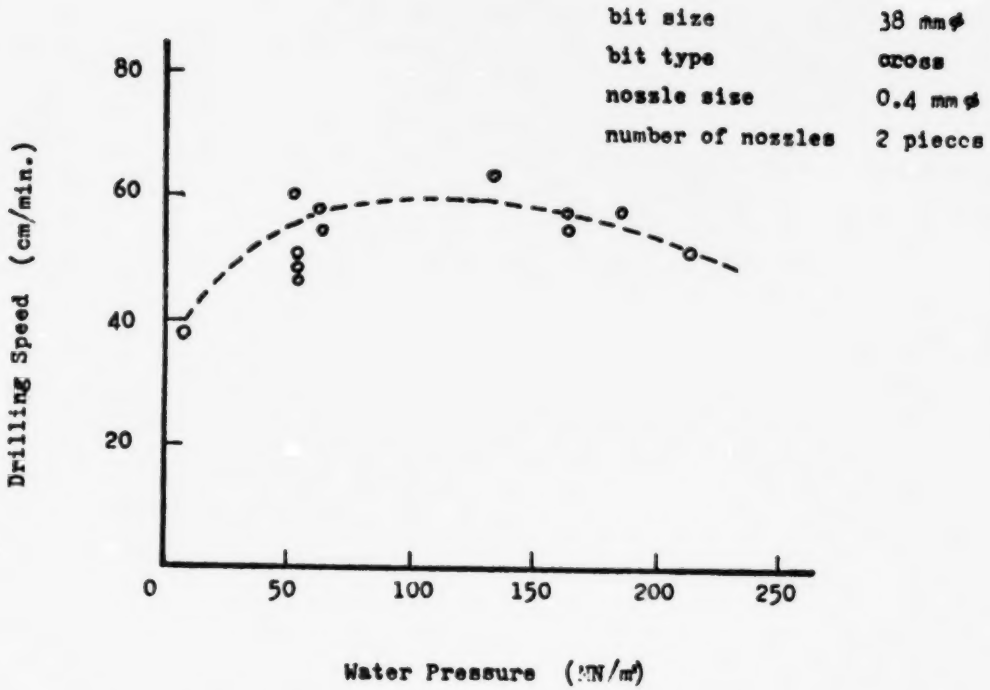


Figure C.7.1 The result of the test of the rock drill using low pressure

ANNEX C.8

WATER-ABRASIVE JET CUTTING RESULTS

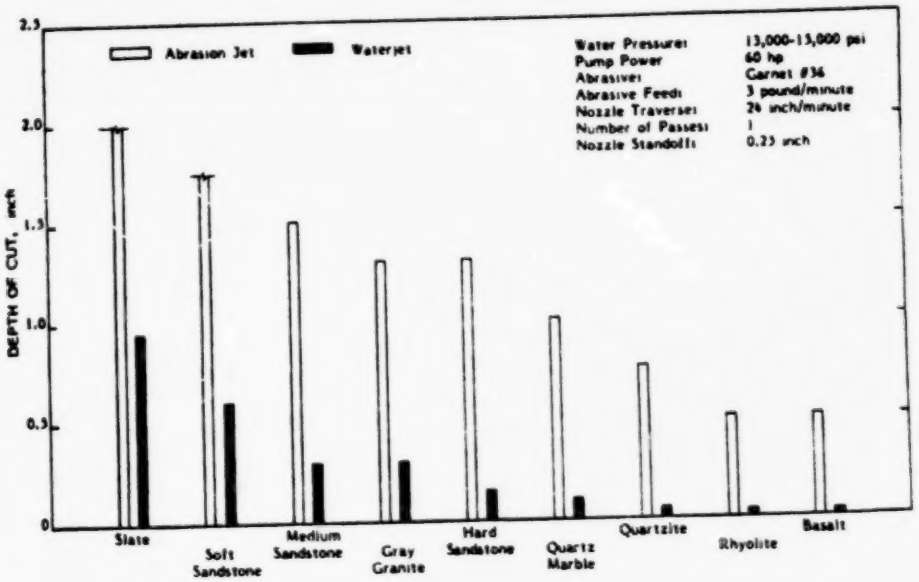


Figure C.8.1 Comparison of depth of cut made on various rock specimens

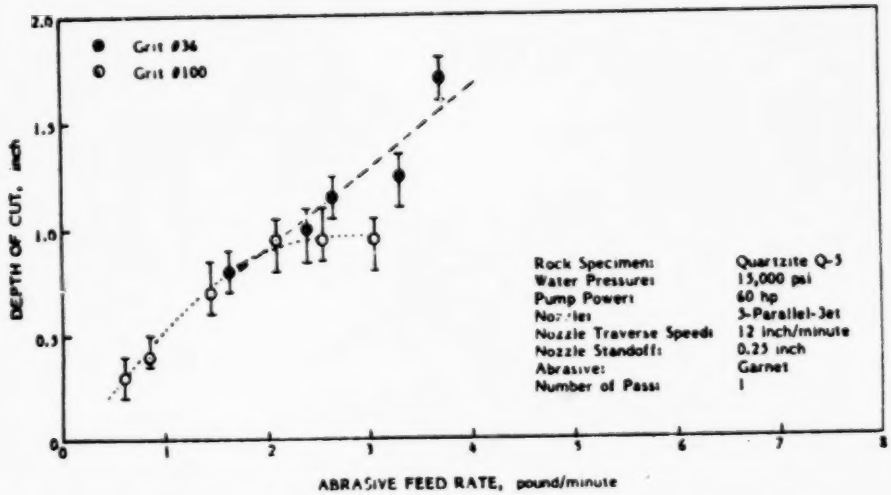


Figure C.8.2 Effect of abrasive feed rate and grain size on depth of cut

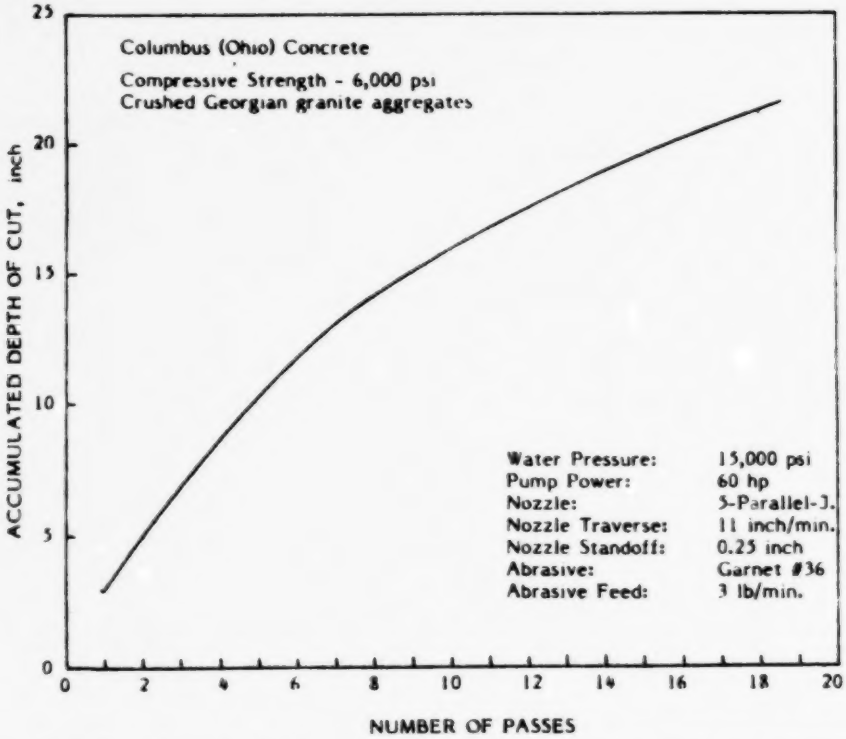


Figure C.8.3 Accumulated depth of multiple-pass cut on concrete

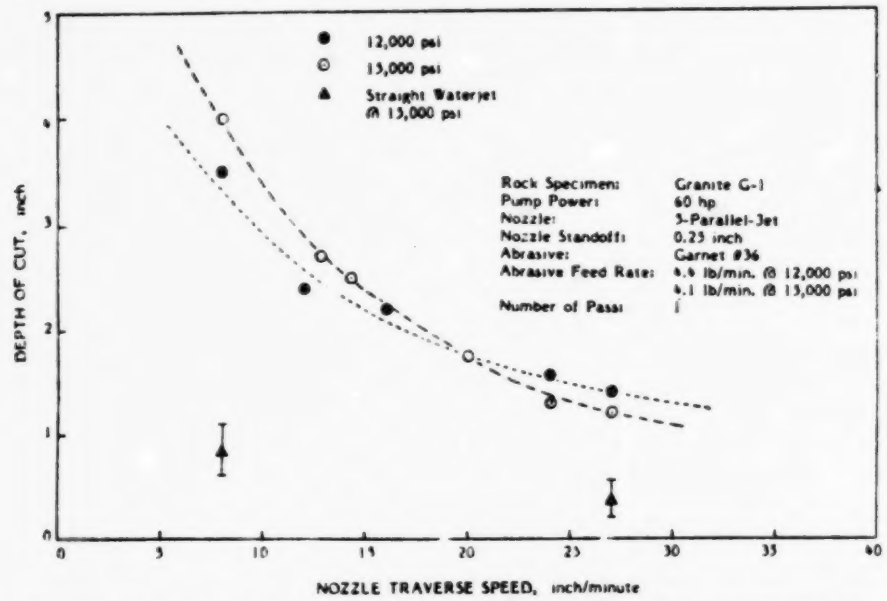


Figure C.8.4 Depth of cuts made on a granite specimen at various nozzle traverse speeds

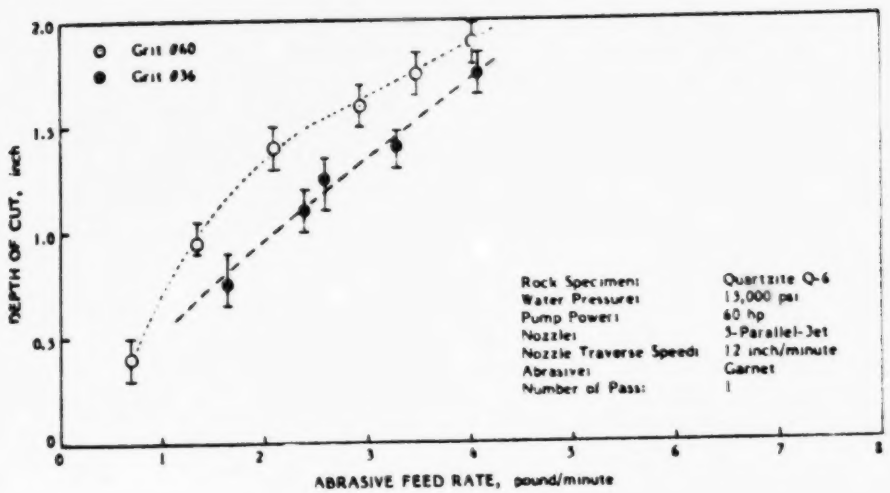


Figure C.8.5 Depth of cuts made on a quartzite Q-6 specimen at various nozzle traverse speeds.

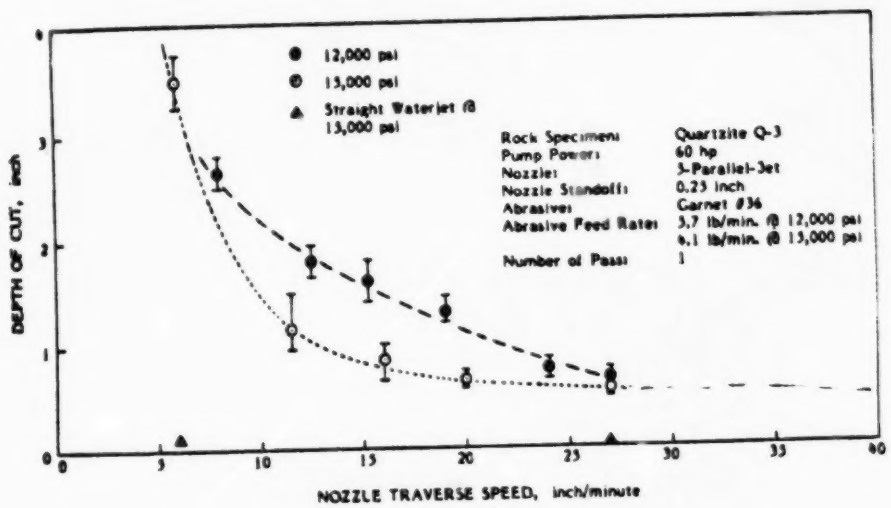


Figure C.8.6 Depth of cuts made on a quartzite Q-3 specimen at various nozzle traverse speeds.

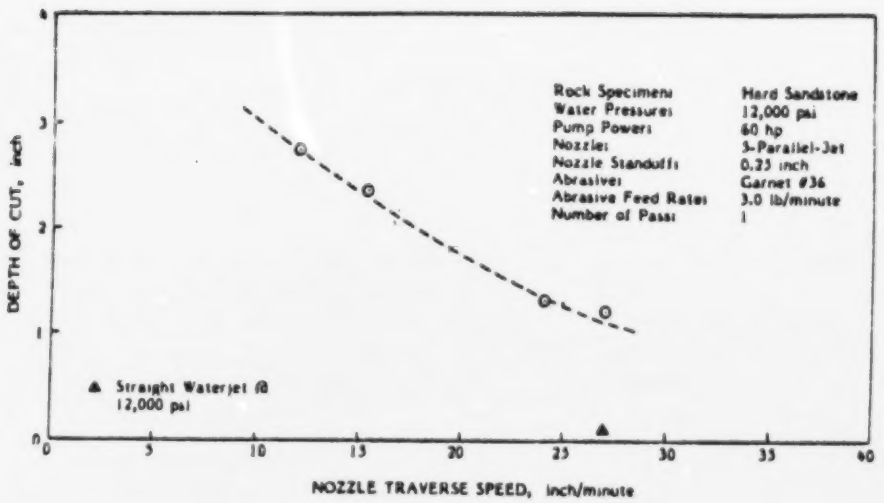
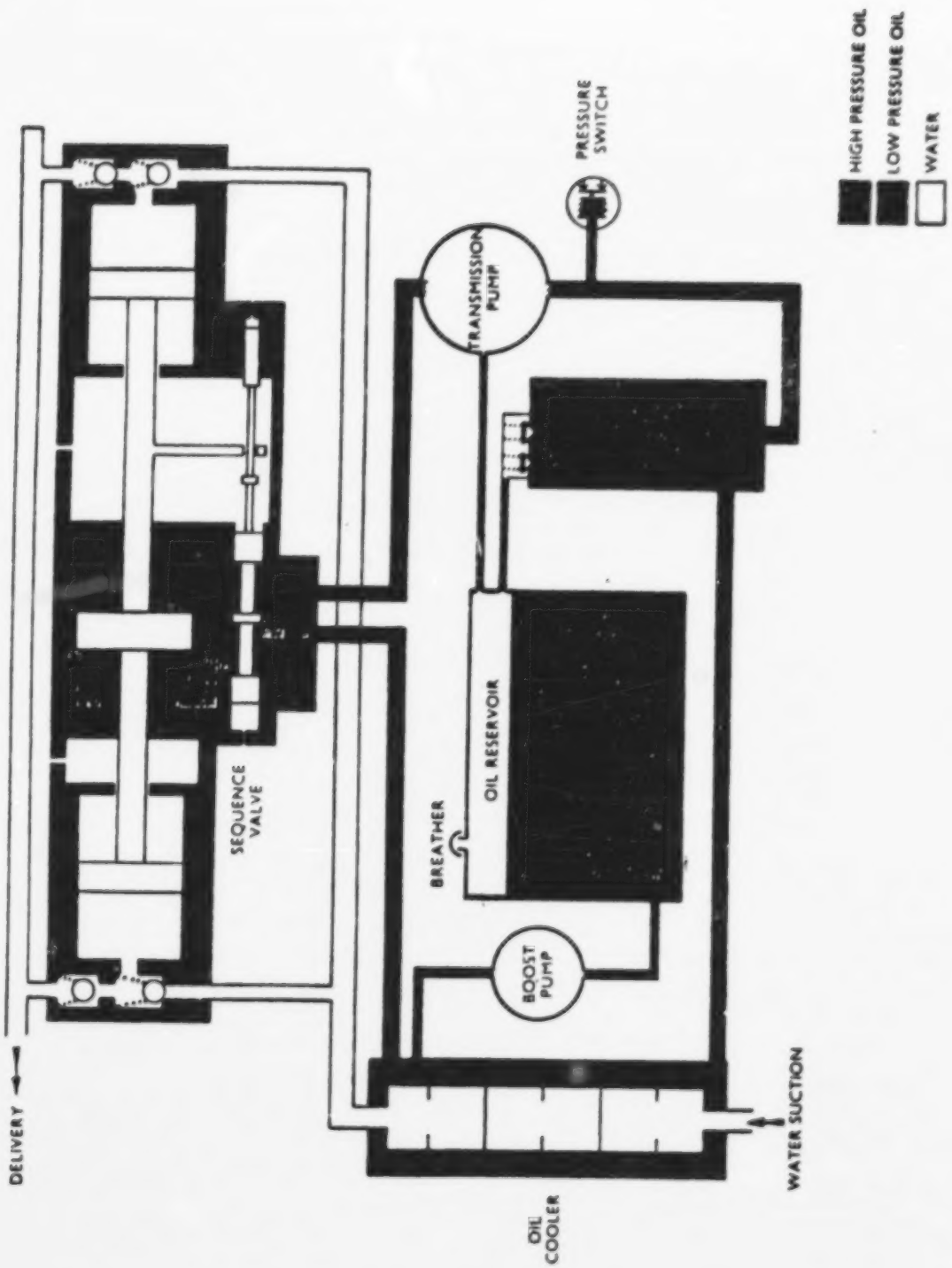


Figure C.8.7 Depth of cuts made on a hard sandstone specimen at various nozzle traverse speeds.

ANNEX C.9

INTENSIFIER PUMP SCHEMATIC


HIGH PRESSURE OIL
LOW PRESSURE OIL
WATER
PRESSURE SWITCH
TRANSMISSION PUMP
SEQUENCE VALVE
BREATHER
OIL RESERVOIR
BOOST PUMP
DELIVERY
WATER SUCTION
OIL COOLER

APPENDIX D

A SUMMARY OF THE GEOLOGY OF THE MAIN RAILWAY CORRIDORS IN WESTERN CANADA

C.J. Boon
Research Associate
Canadian Institute of Guided Ground Transport

D.1 INTRODUCTION D.1

D.2 GENERAL GEOLOGY D.1

1. INTRODUCTION

This overview is intended to provide a general assessment of the bedrock geology and major structural features of those areas which are likely to require significant tunnelling to improve existing rail lines or to construct new lines. Attention has been focussed on conditions adjacent to existing major rail lines, between tidewater on the west coast of British Columbia and Edmonton and Calgary in Alberta, including the interior B.C. lines of the British Columbia Railway. Geological information was extracted from Geology and Economic Minerals of Canada, Parts B and C (Geological Survey of Canada, R.J.W. Douglas, Scientific Editor, 1976).

It must be stressed that an accurate assessment of tunnelling conditions requires a large amount of very site-specific data; inevitably, the generalizations presented here will be inadequate for any specific application. However, as a first-order measure of the general conditions which prevail, this approach will be adequate.

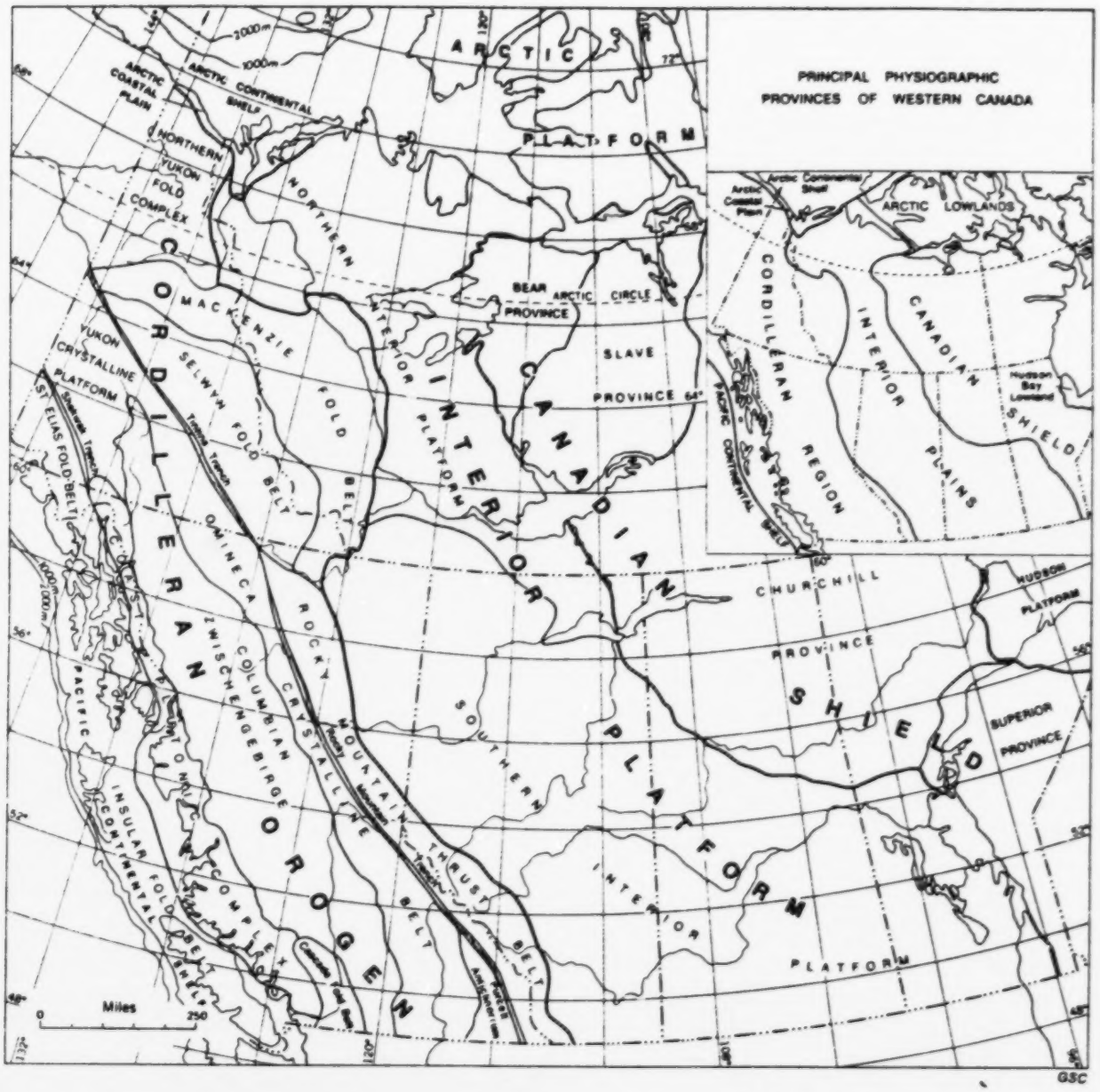
2. GENERAL GEOLOGY

Figure 1 illustrates the principal geological elements of western Canada [Fig. VIII-1, p. 368]. The area of particular concern for tunnelling applications involves the southern and central portions of the Cordilleran Orogen.

The Cordilleran Orogen forms part of the circum-Pacific orogenic belt. It is a region, some 500 miles wide, of mountains and plateaux, trenches, valleys, and fiords. Parts are heavily forested, dry grassland or tundra. Numerous peaks project above timberline or grassline and many bear glaciers.

The eastern part of the orogen embraces the parts of Cordilleran Geosyncline that generally received medium- to fine-grained clastic and carbonate sediments and that underwent surficial deformation with little or no metamorphism, volcanism, or plutonism during the orogenic phases.

The region is divisible into three main sectors. The southernmost sector, the Rocky Mountain Thrust Belt, was produced by the



(after Douglas et al.)

Figure D.1 Principal geological elements of Western Canada

Columbian and Laramide Orogenies during the Cretaceous and early Tertiary. The dominant structures are subparallel, west-dipping thrust faults that produce a series of narrow, linear mountain ranges formed of resistant Paleozoic carbonates. The mountains are bordered, on the east, by the Foothills belt of deformed Mesozoic and Tertiary clastic sediments. In the more southerly parts, very closely spaced thrust faults are characteristic, whereas in the central and northern Foothills they are less prominant and open and tight folds are more typical.

The western part of the Orogen embodies the parts of the Cordilleran Geosyncline that received medium to very coarse clastic sediments. This belt was at times dominated by northwesterly elongate troughs separated by geanticlines; the latter were repeatedly the site of regional metamorphism, granitic emplacement, and intense deformation. The deformation of the rocks in the troughs was controlled largely by their lithology; where volcanic rocks are predominant, broad folds, warps, and numerous steep faults developed, whereas the sedimentary rocks were deformed principally by folding and locally by thrusting. During deformation of these geanticlines, the adjacent basins received thick assemblages of rapidly deposited, marine and non-marine, clastic sediments and minor volcanic rocks. These deposits were subsequently folded and faulted. Pre-orogenic, slightly deformed, continental, clastic and volcanic rocks were deposited locally in fault troughs and are commonly associated with extensional zones of normal faults. Late Tertiary and Pleistocene clastic sediments occur along the Pacific Continental Shelf and parts of the Coastal Plain.

The two belts of crystalline rocks, the Coast Plutonic Complex and the Omineca Crystalline Belt, have been generally positive geanticlines since mid-Paleozoic time. They merge northwestward to form the Yukon Platform. The western or Coast Plutonic Complex is composed predominantly of granitic rocks. It and the Cascade Fold Belt have gneiss-migmatite cores. Both belts were affected by a mid-Paleozoic orogeny, and by a later phase of the Laramide Orogeny. The eastern or Omineca Crystalline Belt includes extensive areas of metamorphic rocks that form the core zone of an alpine-type orogen, the marginal zone of which is the Eastern Cordilleran Orogen. Part of the belt was formed during the Hadrynian East Kootenay Orogeny and the Upper Devonian to Mississippian Caribooan Orogeny. Most was redeformed during the

Tahltanian and Columbian Orogenies. In the south, the eastern and western parts of the Cordilleran Orogen are separated by the Rocky Mountain Trench, a linear erosional zone partly controlled by normal faults.

Columbian Zwischengebirge between the Omineca Crystalline Belt and the Coast Plutonic Complex is structually heterogeneous, but dominated by an elongate northwest-trending belt of disconnected upthrust blocks and by two broad transverse arches. Thick eugeosynclinal sedimentary and volcanic rocks were deposited during the late Paleozoic and early Mesozoic, partly synchronously with orogeny in the bordering crystalline belts. Deposition was locally interrupted by Triassic and Jurassic orogeny activity. As a result of the last period of mountain-building, the region was segmented into three basins, the sediments of which were subsequently folded and block faulted. In the Tertiary, this area was subjected to transcurrent and normal faulting and extensive sheets of basic volcanic rocks were extruded. The early Tertiary volcanism was coeval with emplacement of small high-level granitic plutons.

The Cordilleran Orogen of Canada is one of great geological variety and complexity that developed during the evolution of the Cordilleran Geosyncline from mid-Proterozoic to Recent. At present the region is tectonically quiet, relative to other parts of the circum-Pacific orogenic belt.

These areas contain most major rock types, from clean limestones through the coarsest clastic sediments, a wide variety of extrusive and intrusive igneous rocks, and low- to high-grade metasedimentary and metavolcanic rocks. The resistance to tunnelling posed by these very varied materials is a function of many factors, including:

- mineralogy
- grain size
- degree of induration
- degree of metamorphism
- macro- and micro-scale structural features
- depth of weathering
- presence/absence of ground water.

In practical terms, these factors combine to give each rock type its characteristic ranges of compressive strength and erodibility. It is these measures which are of particular concern in tunnelling, together with any macroscopic structural features (faults, large-scale joints, karst features, etc.) which may be present.

Table D.1 summarizes "typical" uniaxial compression strengths for a variety of rock types. The very substantial variability of the average strength for rocks with the same name points up the need for very site-specific investigations. These variations are the result of changes in the factors noted above (and, perhaps, of a somewhat cavalier application of rock names).

TABLE D.1

UNIAXIAL COMPRESSION TEST RESULTS ON ROCK SUBSTANCES

Rock	Rock Type	Uniaxial Compressive Strength (average) (psi)	Coefficient of Variation (per cent)	Modulus of Deformation (psi (10^6))
Limestone	Sed	15,500	21	8.8
Limestone	Sed	4,960	40	5.4
Sandstone	Sed	31,100	26	4.3
Shale	Sed	5,200	37	3.9
Siltstone	Sed	3,500	66	1.9
Granite	Ig	21,580	33	5.2
Granite	Ig	6,190	27	3.0
Tuff	Ig	38,100	30	11.1
Tuff	Ig	530	21	0.2
Lava	Ig	14,700	32	9.0
Horneblend Schist	Met.	35,400	49	12.7
Jasperoid		64,000	8	12.8
Conglomerate	Sed	31,000	4	10.8
Quartzite	Met.	37,000	16	11.6
Sedenite		32,800	19	18.2

From: "Rock Mechanics Principles."
D.F. Coates, Canmet,
EM&R Canada, Monograph 874-1981.

Tables D.2(a) and D.2(b) provide actual experimentally determined compressive strengths for a range of common rock types for locations around the world (but not, unfortunately, Canada).

The highest compressive strengths are associated with extremely fine-grained sedimentary rocks such as chert (84,000 psi), and aphanitic colloidal precipitate of silica and dolomite (up to 73,000 psi), or with fine-grained igneous rocks such as the Frederik diabase (83,000 psi), coarser-grained igneous and metamorphic rocks such as granite, gneiss, gabbro, amphibolite, quartzite and quartzdiorite from the second rank, along with some particularly well-cemented sandstones and very fine-grained massive limestones (25,000 to 50,000 psi), as a group. Most limestones, sandstones and mudstones, and the corresponding meta-sediments, fall below 20,000 psi, and a significant number below 10,000 psi.

In terms of erodibility, finer-grained igneous and metamorphic rocks (dolerites, quartzites, some granites, gabbros, gneiss, quartz-deorite, amphibolite) are most resistant, followed by well-cemented siliceous sandstones, and coarser-grained igneous and metamorphic rocks. Sedimentary and metasedimentary rocks composed of soft (less than 4 on Moh's scale) minerals, such as limestone, marble, dolomite, shale, and mudstone are most readily eroded.

The new Rogers Pass tunnel now under construction by CP must contend with the rocks of the Selkirk Fan Structure, a major anticlinorial cleavage fan of folded and thrust-faulted metasediments. The tunnel will be partly in the relatively incompetent slaty and dirty carbonate rocks of the Upper Paleozoic Horsethief Creek Gap formation, which forms the base of Mt. Macdonald, and partly in the overlying Lower Cambrian quartzites of the Hamill formation. The rocks of the Horsethief Creek Gap formation are quite weak, but the cliff-forming quartzites are resistant. The incompetence of the Upper Paleozoic strata may cause stability problems within the bore, but there are numerous techniques available to deal with such problems.

TABLE 2(a)

ANALYSIS OF ROCK FRACTURE DATA

Rock type	Name/Location	Author			Uniax. comp. strength, σ_c		each sample		Rock type	
					lb/in^2	MPa	m	r^2	m	r^2
AMPHIBOLITE	Norway (// to foliation)	Broch[138]	●	5	21290	146.8	24.8	0.98	25.1	0.98
	Norway (⊥ to foliation)	Broch[138]	■	5	29240	201.6	21.8	0.99		
CHERT	Chert dyke, South Africa	Hoek[139]	●	24	84040	579.5	20.3	0.93	20.3	0.93
DOLERITE	Frederick diabase, USA	Brace[140]	▲	7	82970	572.1	15.1	0.97		
	Witwatersrand, South Africa	Hoek[139]	■	6	48660	335.5	10.7	0.90	15.2	0.97
	Northumberland, UK	Franklin & Hoek[130]	●	38	42580	293.6	13.4	0.92		
DOLOMITE	Webatuck, USA	Brace[140]	●	6	*	*	7.9	0.95		
	Blair, USA	Brace[140]	■	10	73430	506.3	5.9	0.84	6.8	0.90
	Dunham, USA	Mogi[141]	▲	9	42290	291.6	8.0	0.99		
GABBRO	Norway (dry)	Broch[138]	●	5	50880	350.8	17.3	0.98	23.9	0.97
	Norway (saturated)	Broch[138]	■	5	29730	205.0	22.9	1.00		
GNEISS	Norway (// to foliation)	Broch[138]	●	5	36820	253.9	29.8	0.98	24.5	0.91
	Norway (⊥ to foliation)	Broch[138]	■	5	34010	234.5	21.2	0.96		
GRANITE	Westerley, USA	Heard et al[142]	■	17	31040	214.0	26.7	1.00		
	Westerley, USA	Wawersik & Brace[143]	▲	7	43310	298.6	27.0	1.00		
	Westerley, USA	Brace[140]	▼	7	49820	343.5	28.3	0.98		
	Westerley, USA	Mogi[141]	►	6	32440	223.7	32.8	0.99	29.2	0.99
	Stone Mountain, USA	Schwartz[137]	◄	14	16850	116.2	28.9	0.93		
	Blackingstone, UK	Franklin & Hoek[130]	●	48	30410	209.7	20.8	0.91		
	Mount Sorrel, UK	Misra[144]	●	5	39910	275.2	26.5	0.99		
	Carnmarth, Redruth, UK	Misra[144]	◆	5	23540	162.3	27.7	0.99		
LIMESTONE	Portland, UK	Franklin & Hoek[130]	◆	30	13300	91.7	7.5	0.72		
	Indiana, USA	Schwartz[137]	■	6	7090	48.9	3.2	0.95		
	Bath, UK	Misra[144]	●	7	6830	47.1	5.5	0.97		
	Grindling Stubbs, UK	Misra[144]	●	6	19450	134.1	8.8	0.97		
	Kirbymoorside, UK	Misra[144]	●	5	23830	164.3	12.3	0.98		
	Blackwell, UK	Misra[144]	●	5	29211	201.4	10.0	0.92	5.4	0.68
	Foster Yeoman, UK	Misra[144]	●	5	24265	167.3	14.1	0.95		
	Guiglewick, UK	Misra[144]	●	5	22423	154.6	8.8	0.97		
	Kelmac, UK	Misra[144]	●	5	16897	116.5	7.3	1.00		
	Threshfield, UK	Misra[144]	●	5	21423	147.7	6.9	0.98		
	Swinden Cracoe, UK	Misra[144]	●	5	16027	110.5	8.4	0.96		

From: "Underground Excavation in Rock." W. Hock and E.T. Brown, The Institution of Mining and Metallurgy, London, England, 1980

TABLE 2(b)

ANALYSIS OF ROCK FRACTURE DATA (cont'd)

Rock type	Name, location	Reference	Symbol	No. of tests	Uniax. comp. str. at mean fail. stress		Tan. comp.		Tensile	
					lb/in²	MPa	m	r²	m	r²
MARBLE	Tennessee II , USA	Wawersik & Fairhurst[145]	●	44	19330	133.3	.9	.99		
	Norwegian	Broch[136]	■	5	8370	57.7	.2	1.00		
	Carrara, Italy	Kovari & Tisa[146]	◆	26	15050	103.8	6.6	0.99	10.6	0.90
	Carrara, Italy	Franklin & Hoek[130]	▼	14	13590	93.7	7.7	0.99		
	Carthage, USA	Bredthauer[147]	▲	7	9060	62.5	11.7	0.95		
	Georgia, USA	Schwartz[137]	◀	9	7210	49.7	7.1	0.98		
MUDSTONE	South Africa	Bieniawski[148]	●	29	*	*	7.3	0.85	7.3	0.82
	Horton-in-Ribblesdale, UK	Misra[144]	■	5	18910	130.4	11.1	1.00		
NORITE	South Africa	Bieniawski[148]	●	17	*	*	23.3	0.97	23.2	0.97
QUARTZDIORITE	Norway (dry)	Broch[136]	●	5	35210	242.8	20.2	1.00	23.4	0.98
	Norway (saturated)	Broch[136]	■	5	27160	187.3	23.8	0.99		
QUARTZITE	Witwatersrand, South Africa	Hoek[139]	●	19	32860	226.6	14.1	0.99		
	Witwatersrand, South Africa	Bieniawski[148]	■	35	*	*	18.5	0.82	16.8	0.84
	Boons Nuneaton, UK	Misra[144]	▼	5	47450	327.2	23.3	1.00		
SANDSTONE	Berea, USA	Aldrich[149]	●	27	10540	72.7	15.0	0.99		
	Pottsville, USA	Schwartz[137]	■	44	12970	89.4	19.3	0.87		
	South Africa	Bieniawski[148]	◆	56	7820	53.9	18.6	0.90		
	Derbyshire, UK	Franklin & Hoek[130]	▼	33	8950	61.7	15.6	0.93		
	Darley Dale, UK	Franklin & Hoek[130]	▲	27	11660	80.4	15.9	0.99		
	Pennant, UK	Franklin & Hoek[130]	◀	31	30310	209.0	11.9	0.98		
	Nugget, USA	Schock et al[150]	▶	13	57780	398.4	15.3	0.96		
	Buchberg, Switzerland	Kovari & Tisa[146]	●	47	10070	69.4	14.3	0.87		
	Mév, Hungary	Bodonyi[151]	○	14	12110	83.5	22.5	0.84	14.3	0.87
	Elland Edge, UK	Misra[144]	□	6	14910	102.8	12.8	0.99		
	Darley Dale, UK	Misra[144]	▽	11	6630	45.7	12.5	1.00		
	Bretton Blue, UK	Misra[144]	△	6	25950	178.9	7.4	0.99		
	Horsforth, UK	Misra[144]	◁	5	7006	48.3	16.7	1.00		
	Ramsbottom Wild, UK	Misra[144]	▷	5	15288	105.4	17.7	1.00		
	Buckstone, UK	Misra[144]	◇	5	14359	99.0	27.3	1.00		
	St Bees, UK	Misra[144]	▲	7	9780	67.4	9.2	0.98		
	Darley Dale, UK	Ramez[152]	◐	28	14780	101.9	8.8	0.97		
	Darley Dale, UK	Price[154]	◐	5	5780	39.9	6.4	0.85		
	Gosford, Australia	Jaeger[153]	◙	5	9010	62.1	15.7	0.99		

* *Quoted in dimensionless form in original paper.*

From: "Underground Excavation in Rock." W. Hock and E.T. Brown, The Institution of Mining and Metallurgy, London, England, 1980

APPENDIX E

OPERATIONS COST ANALYSIS

P. White, P.Eng.
Brampton Mining

This appendix summarizes the economic analysis of high-pressure water jet technology in a railway tunnelling environment in British Columbia, for which the costs and operating statistics were available and current.

Recent railway tunnelling projects in British Columbia include the Tumbler Ridge Branch Line which was constructed to service the northeastern coal regions. These tunnels were driven using conventional drill-and-blast tunnelling methods using hydraulically-powered rock drills for blasthole drilling.

The driving of railway tunnels under similar working conditions was examined to assess the sensitivity of tunnelling costs to the application of high-pressure water jet drilling techniques. Cost estimates and schedules (Tables E.2 through E.11) were prepared for the following cases:

- conventional drill-and-blast pilot tunnel and bench
- conventional drill-and-blast full-face tunnel
- conventional full-face tunnel-boring machine
- water-jet-assisted drill-and-blast full-face tunnel
- water-jet-assisted full-face tunnel-boring machine

The use of roadheading equipment was not considered due to the lower performance of these machines with respect to drill-and-blast and TBM methods. The results of the cost analysis are shown in Table E.1.

From Table E.1, the use of conventional TBM equipment appears to provide the lowest overall cost of driving 3,000 metres of railway tunnel. TBM equipment, with an average advance rate of 24 metres per day, provides a 20 per cent reduction in tunnelling costs when compared with drill-and-blast methods with an average advance rate of 14 metres per day.

The incorporation of water jet blasthole drilling into the drill-and-blast tunnelling method shows only a marginal reduction in tunnelling costs, but does provide an overall reduction of 13 per cent in the time to complete the tunnel due to the improved advance rate.

In the case of TBM methods, the improvement in tunnelling advance from 24 to 40 metres per day when water-jet-assisted cutting is

TABLE E.1

TUNNELLING METHOD EVALUATION SUMMARY

Item	Conventional			Water-Jet-Assisted	
	Pilot/ Bench	Full-Face	TBM	Full-Face	TBM
Tunnel Dimensions:					
Optimum length	<1,500 m	<1,500 m	<1,500 m	<1,500 m	<1,500 m
Length costed	1,000 m	3,000 m	3,000 m	3,000 m	3,000 m
Tunnel size	5.4 m x 7.3 m	5.4 m x 7.3 m	7.3 m dia.	5.4 m x 7.3 m	7.3 m dia.
Tunnelling performance:					
Average (m/day)	16.8	14	24	17.6	40
Maximum (m/day)	30.0	18	35-40	22.0	60-65
Tunnelling costs per metre of tunnel:					
Mobilization	$ 600	$1,667	$2,000	$1,867	$2,333
Excavation	5,461	5,951	3,974	5,464	3,984
Total Unit Costs	$6,061	$7,618	$5,974	$7,331	$6,317
Tunnelling costs per cubic metre excavated:					
Total Unit cost	$ 168	$ 211	$ 142	$ 204	$ 150
Tunnel excavation schedules:					
Days to complete	123	335	305	291	255
Tunnel crew size:					
Daily manpower	30	60	39	60	45

considered, is offset by additional manpower- and equipment-related costs. In the case considered, the cost of water-jet-assisted TBM operation is marginally higher than for conventional TBM methods. Despite this marginally higher cost, however, the overall project duration is reduced by over 16 per cent when water-jet-assisted cutting is employed.

The preceding cost estimates reflect the following assumptions, based on the methods and procedures used during construction of the Tumbler Ridge tunnels in British Columbia:

- Typical heavy construction union regulations apply.
- Labour costs based on union working practices.
- Costs of all contractor-supplied excavation equipment included in mobilization costs.
- Costs of contractor-supplied electric power included in mobilization and excavation costs.
- Cost of owner-supplied engineering and project management not included.
- Cost of owner-supplied site access roads and camp facilities not included.
- Cost of ancillary equipment such as surface fans, air heaters, contractors' offices, surface equipment and ground support equipment is not included as these are assumed to be similar for all methods considered.
- Cost of ground support not included in cost estimate as these do not impede tunnelling advance.

The tunnelling costs assume that the drill-and-blast tunnel is driven in the classical horseshoe shape, 5.4 metres wide and 7.3 metres high with a semicircular back. In the case of TBM equipment, a machine diameter of 7.3 metres is assumed. The drill-and-blast tunnel requires the excavation of 36 cubic metres of rock per metre of tunnel length, compared with 42 cubic metres per metre for the TBM equipment.

KEY ASSUMPTIONS

As previously stated, the pilot heading and bench tunnelling method is the most appropriate technique for the construction of short railway tunnels of less than 1,500 metres. The competition between contractors for shorter tunnels is increased due to the fact that most of the necessary tunnelling equipment is available from other tunnelling jobs, or readily available on the used equipment market. This leads to reduced mobilization time periods and lower equipment rental costs than is the case with the use of new tunnelling equipment.

In the case of the longer tunnels, the types of equipment required are seldom readily available, thus requiring contractors to have the drill jumbos custom manufactured. This adds to the cost of mobilization and setup and requires additional lead time to initiate the project.

Equipment such as the Conway mucker and the TBM is assumed to be used, reconditioned machines, since the long lead time and high cost of building new equipment are prohibitive in terms of meeting a competitive price and schedule. Other equipment such as locomotives, compressors and ancillary equipment is assumed to be available within the equipment fleets of the tunnelling contractors.

The labour requirements and labour costs for this project are based on satisfying heavy construction union regulations and working practices. The daily cost of $500 per man-day is inclusive of room and board, overtime premiums and overtime pay to accommodate extra working hours in order for the face operations to run on a continuous basis.

The cases involving water-jet-assisted tunnelling include the costs of engineering and assembling the necessary components to accommodate the high-pressure pumps and control valves. These front-end engineering costs have been included in addition to the purchase and installation costs in order to reflect the full cost structure that will be applicable to any field trial.

In the case of water-jet-assisted drill-and-blast tunnelling methods, the penetration rate of the drilling equipment is assumed to be increased by 50 per cent. To take full benefit of the higher penetration rate, it is

further assumed that the blasthole length is increased by an extra metre over the case with conventional drilling equipment. Due to the increased blasthole length, the time required to load explosives and to muck out are also increased. This requires the same overall cycle time as for conventional drilling, but results in an increase in the daily advance rate.

In the case of water-jet-assisted TBM tunnelling methods, the performance improvement was assumed to be 67 per cent increase in the tunnelling rate compared with conventional TBM methods. In both TBM cases, the effective number of operating hours was assumed to be eight hours per day, with the remaining time allocated to TBM maintenance, adjustments and ancillary (non-rotating) tunnelling activities.

In the water-jet-assisted TBM case, it was assumed that the cutter life was increased by 40 per cent, thereby contributing to lower cutter costs and reduced time requirements for cutter maintenance, normally a major source of TBM downtime. Additional costs were assumed to be incurred, however, as a result of problems with the high-pressure pumps, controls, piping, hoses, fittings and seals. The additional cost of water-jet-related maintenance repair parts and labour requirements substantially offset the reduced cutter costs and the benefits achieved in increased TBM performance.

The preceding assumptions and cost analyses are based on the consideration of typical tunnel construction conditions applicable to the excavation of railway tunnels in British Columbia. The conclusions drawn from these examples will change based on site-specific tunnelling conditions, design parameters and geological environments.

TABLE E.2

CASE #1: PILOT HEADING AND BENCH - DESIGN CRITERIA

Tunnel length: 1,000 metres, with access from both portals.

Tunnelling equipment:

2 three-boom hydraulic drill jumbos
4 front-end loaders (Cat 988 class)
2 air compressors (300 l/s class)
2 diesel generators (500 kW)

Tunnelling crew:

Classification	Day	Afternoon	Night	Total
Driller	2	2	2	6
Chucktender	1	1	1	3
Loader Operator	2	2	2	6
Teamster	1	1	1	3
Mechanic	2	2	2	6
Electrician	1	1	1	3
Supervisor	1	1	1	3
Total crew	10	10	10	30

Tunnelling performance:

Pilot heading:
- drill 71 4.6-metre blastholes
- break 4.2 metres per round
- cycle time per round = 9 hours (drilling = 3 hrs; loading = 1 hr; mucking = 3 hrs; services = 2 hrs)
- assuming two faces, one from each portal, average advance is four rounds per day on the a three-shift basis

Bench:
- assuming that the bench is drilled off using vertical blastholes, average advance will be 30 metres per day working from one portal

Project duration:
- mobilization = 20 days
- pilot, 1,000 m @ 16.8 m/d = 60 days
- bench, 1,000 m @ 30 m/d = 33 days
- demobilization = 10 days
- total duration = 123 days

TABLE E.3

CASE #1: PILOT HEADING AND BENCH - COST CALCULATION

Pilot heading at 16.8 metres advance per day:

	Cost/metre
Labour - 30 men at $500 per man-day	$ 893
Equipment rentals for excavation equipment	298
Equipment repairs	383
Operating supplies (fuel/lube; steel/bits)	383
Tunnel supplies (pipe; electric cable)	128
Explosives	700
Miscellaneous items	128
Subtotal	$2,913
Contractor's markup	728
Total, pilot heading cost per metre	$3,641

Bench excavation at 30 metres advance per day:

	Cost/metre
Labour - 30 men at $500 per man-day	$ 500
Equipment rentals for excavation equipment	167
Equipment repairs	200
Operating supplies (fuel/lube; steel/bits)	200
Tunnel supplies (pipe; electric cable)	nil
Explosives	300
Miscellaneous items	88
Subtotal	$1,455
Contractor's markup	365
Total, bench excavation cost per metre	$1,820

Cost Summary:

Pilot and bench cost per metre of tunnel	$5,461
Mobilizaton cost per metre of tunnel	600
Total tunnelling cost per metre	$6,061

TABLE E.4

CASE #2: FULL-FACE CONVENTIONAL DRILL-AND-BLAST - DESIGN CRITERIA

Tunnel length: 3,000 metres, with access from one portal

Tunnelling equipment:

1 six-boom hydraulic rail-mounted drill jumbo and service platform with two decks
2 Conway or Hagglund loaders
3 locomotives (20 tonne class)
12 muck cars (11 cubic metre capacity)
1 sliding floor (magic carpet)
1 air compressor (300 l/s class)
1 lot of transformers and switchgear
2 diesel generators (500 kW)

Tunnelling crew:

Classification	Day	Afternoon	Night	Total
Driller	4	4	4	12
Chucktender	2	2	2	6
Mucker	2	2	2	6
Serviceman	4	4	4	12
Switchman	1	1	1	3
Loci driver	2	2	2	6
Teamster	1	1	1	3
Mechanic	2	2	2	6
Electrician	1	1	1	3
Supervisor	1	1	1	3
Total crew	20	20	20	60

Tunnelling performance:

Drill 105 3.7-metre blastholes
Break 3.5 metres per round
Cycle time per round: 5 hours (drilling = 2 hrs; loading = 1 hr; mucking = 2 hrs; services = concurrently)
Maximum advance rate: 18 metres per day
Average advance rate: 14 metres per day
Project duration:

. mobilization	60 days
. excavation	215 days
. remove services	30 days
. demobilization	30 days
. total duration	335 days

TABLE E.5

CASE #2: FULL-FACE CONVENTIONAL DRILL-AND-BLAST - COST CALCULATION

Mobilization cost:

6 boom drill jumbos	$1,500,000
2 Conway muckers	1,000,000
Sliding floor	1,000,000
Locomotives and cars	500,000
Freight and setup	1,000,000
Total mobilization cost	$5,000,000

Description:

	Cost/Metre
Labour - 60 men at $500 per man-day	$2,143
Miscellaneous equipment rentals	238
Equipment repairs	476
Operating supplies (fuel/lube; steel/bits)	476
Tunnel supplies (pipe; electric cable)	238
Explosives	952
Miscellaneous items	238
Subtotal	$4,761
Contractor's markup	1,190
Tunnel excavation cost per metre	5,951
Mobilization cost per metre of tunnel	1,667
Total cost per metre of tunnel	$7,618

TABLE E.6

CASE #3: CONVENTIONAL TUNNEL-BORING EQUIPMENT
- DESIGN CRITERIA

Tunnel length: 3,000 metres, with access from one portal

Tunnelling equipment:

1 7.3 metre diameter reconditioned TBM
3 locomotives (25 tonne class)
12 muck cars (17 cubic metre capacity)
1 air compressor (300 l/s class)
1 lot of transformers and switchgear
4 diesel generators (500 kW)

Tunnelling crew:

Classification	Day	Afternoon	Night	Total
TBM operator	1	1	1	3
Serviceman	3	3	3	9
Switchman	1	1	1	3
Loci driver	2	2	2	6
Teamster	1	1	1	3
Mechanic	2	2	2	6
Electrician	2	2	2	6
Supervisor	1	1	1	3
Total crew	13	13	13	39

Tunnelling performance:

Effective penetration rate: 3 metres per hour

Average performance: 24 metres per day

Maximum perforamnce: 35-40 metres per day

Project duration:
- mobilization 90 days
- excavation 125 days
- remove services 60 days
- demobilization 30 days
- total duration 305 days

TABLE E.7

CASE #3: CONVENTIONAL TUNNEL-BORING EQUIPMENT
- COST CALCULATION

Mobilization cost:

Used 7.3 metre diameter TBM	2,500,000
TBM rehabilitation	1,000,000
Locomotives and cars	1,000,000
TBM erection	500,000
Freight and setup	1,000,000
Total mobilization cost	$6,000,000

Description:

	Cost/Metre
Labour - 39 men at $500 per man-day	$ 813
Miscellaneous equipment rentals	238
Equipment repairs	500
Cutter costs ($5/$m^3$ x 42 m^3)	210
Miscellaneous TBM supplies ($1/$m^3$ x 42 m^3)	42
Operating supplies (fuel/lube)	900
Tunnel supplies (pipe; electric cable)	238
Miscellaneous items	238
Subtotal	$3,179
Contractor's markup	795
Tunnel excavation cost per metre	$3,974
Mobilization cost per metre of tunnel	2,000
Total cost per metre of tunnel	$5,974

TABLE E.8

CASE #4: FULL-FACE WATER-JET-ASSISTED DRILL-AND-BLAST - DESIGN CRITERIA

Tunnel length: 3,000 metres, with access from one portal

Tunnelling equipment:

1 six-boom hydraulic rail-mounted drill jumbo and service platform with two decks
2 Conway or Hagglund loaders
3 locomotives (20 tonne class)
16 muck cars (11 cubic metre capacity)
1 sliding floor (magic carpet)
1 air compressor (300 l/s class)
1 lot of transformers and switchgear
2 diesel generators (500 kW)

Tunnelling crew:

Classification	Day	Afternoon	Night	Total
Driller	4	4	4	12
Chucktender	2	2	2	6
Mucker	2	2	2	6
Serviceman	4	4	4	12
Switchman	1	1	1	3
Loci driver	2	2	2	6
Teamster	1	1	1	3
Mechanic	2	2	2	6
Electrician	1	1	1	3
Supervisor	1	1	1	3
Total crew	20	20	20	60

Tunnelling performance:

Drill 105 4.7-metre blastholes
Break 4.4 metres per round
Cycle time per round: 5 hours (drilling = 1.25 hrs; loading = 1.25 hrs; mucking = 2.50 hrs; services = concurrently)
Maximum advance rate: 22 metres per day
Average advance rate: 17.6 metres per day
Project duration:

. mobilization	60 days
. excavation	171 days
. remove services	30 days
. demobilization	30 days
. total duration	291 days

TABLE E.9

CASE #4: FULL-FACE WATER-JET-ASSIST DRILL-AND-BLAST - COST CALCULATION

Mobilization cost:

6 boom drill jumbos	$1,500,000
Water jet equipment	500,000
2 Conway muckers	1,000,000
Sliding floor	1,000,000
Locomotives and cars	600,000
Freight and setup	1,000,000
Total mobilization cost	$5,600,000

Description:

	Cost/Metre
Labour - 60 men at $500 per man-day	$1,705
Miscellaneous equipment rentals	238
Equipment repairs	500
Operating supplies (fuel/lube; steel/bits)	500
Tunnel supplies (pipe; electric cable)	238
Explosives	952
Miscellaneous items	238
Subtotal	$4,371
Contractor's markup	1,093
Tunnel excavation cost per metre	$5,464
Mobilization cost per metre of tunnel	1,867
Total cost per metre of tunnel	$7,331

TABLE E.10

CASE #5: WATER-JET-ASSISTED TUNNEL-BORING EQUIPMENT - DESIGN CRITERIA

Tunnel length: 3,000 metres, with access from one portal

Tunnelling equipment:

1 7.3 metre diameter reconditioned TBM
3 locomotives (25 tonne class)
16 muck cars (17 cubic metre capacity)
1 air compressor (300 l/s class)
2 lots of transformers and switchgear
5 diesel generators (500 kW)

Tunnelling crew:

Classification	Day	Afternoon	Night	Total
TBM operator	1	1	1	3
Serviceman	4	4	4	12
Switchman	1	1	1	3
Loci driver	2	2	2	6
Teamster	1	1	1	3
Mechanic	3	3	3	9
Electrician	2	2	2	6
Supervisor	1	1	1	3
Total crew	15	15	15	45

Tunnelling performance:

Effective penetration rate: 5 metres per hour

Average performance: 40 metres per day

Maximum performance: 60-65 metres per day

Project duration:
- mobilization 90 days
- excavation 75 days
- remove services 60 days
- demobilization 30 days
- total duration 255 days

TABLE E.11

CASE #5: WATER-JET-ASSISTED TUNNEL-BORING EQUIPMENT - COST CALCULATION

Mobilization cost:

Used 7.3 metre diameter TBM	2,500,000
TBM rehabilitation	1,000,000
Water-jet equipment	750,000
Locomotives and cars	1,250,000
TBM erection	500,000
Freight and setup	1,000,000
Total mobilization cost	$7,000,000

Description:

	Cost/Metre
Labour - 45 men at $500 per man-day	$ 563
Miscellaneous equipment rentals	238
Equipment repairs	600
Cutter costs ($5/$m^3$ x 42 m^3)	126
Miscellaneous TBM supplies ($2/$m^3$ x 42 m^3)	84
Operating supplies (fuel/lube)	1,100
Tunnel supplies (pipe; electric cable)	238
Miscellaneous items	238
Subtotal	$3,187
Contractor's markup	797
Tunnel excavation cost per metre	$3,984
Mobilization cost per metre of tunnel	2,333
Total cost per metre of tunnel	$6,317

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